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### Synopsis

Kularatna's new book describes modern component families and how to design circuit blocks using them. While much of this information may be available elsewhere, in *Modern Component Families and Circuit Block Design* it is integrated with additional design hints that are unique. The discussion covers most components necessary in an embedded design or a DSP-based real time system design. The chapter on modern semi-conductor sensors allows system designers to use the latest sensor ICs for real-world physical parameter sensing.

\*Covers the most recent low-power components

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E.M. Aupperle, University of Michigan

...beneficial not only to reinforce their technical foundation, but also to update themselves with the ever-altering electronic component systems technology

- IEEE Circuits and Devices Magazine, Sept./Oct. 2004

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### Synopsis

Microengineering Aerospace Systems is a textbook tutorial encompassing MEMS (micro-electromechanical systems), nanoelectronics, packaging, processing, and materials characterization for developing miniaturized smart instruments for aerospace systems (i.e., ASIM application-specific integrated microinstrument), satellites, and satellite subsystems. Third in a series of Aerospace Press publications covering this rapidly advancing technology, this work presents fundamental aspects of the technology and specific aerospace systems applications through worked examples.

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### 332 Modern Component Families and Circuit Block Design

Control networks provide many benefits for transducers:

- Significant reduction in installation costs by eliminating many and long analog wires.
- Acceleration of control loop design cycles, reduction of commissioning time, and reduction of downtime.
- Dynamic configuration of measurement and control loops via software.
- Addition of intelligence by leveraging the microprocessors used for digital communication.

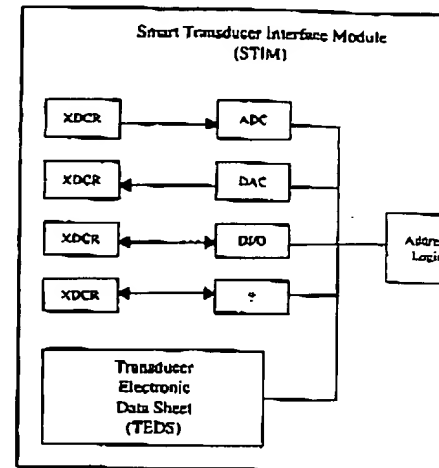
For anyone attempting to choose a sensor-interface or networking standard, the range of choices is overwhelming. Some standards are open, and some are proprietary to a company's control products. To remedy the situation, the IEEE Sensor Technology Committee TC-9 is developing the IEEE P1451, Standard for Smart Transducer Interface for Sensors and Actuators. The sensor market comprises widely disparate sensor types. Designers consume relatively large amounts of all types of sensors. However, the lack of a universal interface standard impedes the incorporation of "smart" features, such as an onboard electronic data sheet, onboard A/D conversion, signal conditioning, device-type identification, and communications hand-shaking circuitry, into the sensors. In response to the industry's need for a communication interface for sensors, the IEEE with cooperation from the National Institute of Standards and Technology (NIST), decided to develop a hardware-independent communication standard for low-cost smart sensors that includes smart transducer object models for control networks (Travis, 1995).

The IEEE P1451 standards effort, currently under development, will provide many benefits to the industry. P1451, "Draft Standard for Smart Transducer Interface for Sensors and Actuators," consists of four parts, namely:

- IEEE 1451.1—Network Capable Application Processor (NCAP) information model,
- IEEE 1451.2—Transducer to Microprocessor Communications Protocols and Transducer Electronic Data Sheet (TEDS) formats,
- IEEE P1451.3—Digital Communication and Transducer Electronic Data Sheet (TEDS) formats for distributed multidrop systems, and
- IEEE 1451.4—Mixed-mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) formats.

In the process of writing the draft document, the working group has defined the smart transducer interface module (STIM), transducer electronic data sheet (TEDS), transducer-independent interface (TII), and a set of communication protocols between the STIM and the network capable application processor (NCAP).

A system block diagram depicting the interface is shown in Figure 7-46. A STIM is specified to include up to 255 transducers, a signal converter or conditioning, a TEDS, and the necessary logic circuitry to support digital communication



**FIGURE 7-46** System block diagram depicting the interface between a STIM and a TEDS (Courtesy of NIST)

with NCAP. The TEDS is a small physical information and data for the transducer in a 10-wire digital interface with provision for read sensors.

Figure 7-47(a) depicts a STIM and is described in the P1451.2-1997 hot swap. The STIM is a network-node microprocessor. In addition, STIMs can be used with microprocessor portable instruments and data acquisition

**TABLE 7-5** The ten lines that make up the STIM (Courtesy of NIST)

Line	Driven by	Function
DIN	NCAP	Address and data transport
DOUT	STIM	Data transport
DCLK	NCAP	Positive-going clock
NIOE	NCAP	Signals that are transported
NTRIG	NCAP	Performs trigger
NACK	STIM	Serves two functions
NINT	STIM	Used by the transducer
NSDET	STIM	Grounded in the presence of a signal
POWER	NCAP	Nominal 5 V
COMMON	NCAP	Signal common

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. sensor-interface or networking standard, Some standards are open, and some are ducts. To remedy the situation, the IEEE s developing the IEEE P1451, Standard nsors and Actuators. The sensor market ces. Designers consume relatively large er, the lack of a universal interface stan- "t" features, such as an onboard electronic gnal conditioning, device-type identifica- g circuitry, into the sensors. In response ion interface for sensors, the IEEE with e of Standards and Technology (NIST), lent communication standard for low-cost luer object models for control networks

currently under development, will provide "Draft Standard for Smart Transducer nsists of four parts, namely:

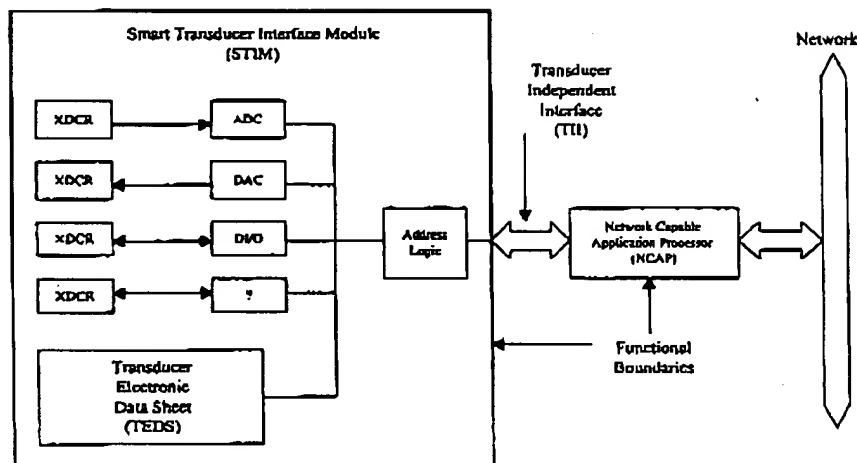
Application Processor (NCAP) informa-

roprocessor Communications Protocols eet (TEDS) formats, ication and Transducer Electronic Data ed multidrop systems, and munication Protocols and Transducer nats.

document, the working group has defined (STIM), transducer electronic data sheet ice (TII), and a set of communication network capable application processor

the interface is shown in Figure 7-46. A transducers, a signal converter or condi- circuitry to support digital communication

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**FIGURE 7-46** System block diagram depicting the transducer interface (Courtesy of NIST)

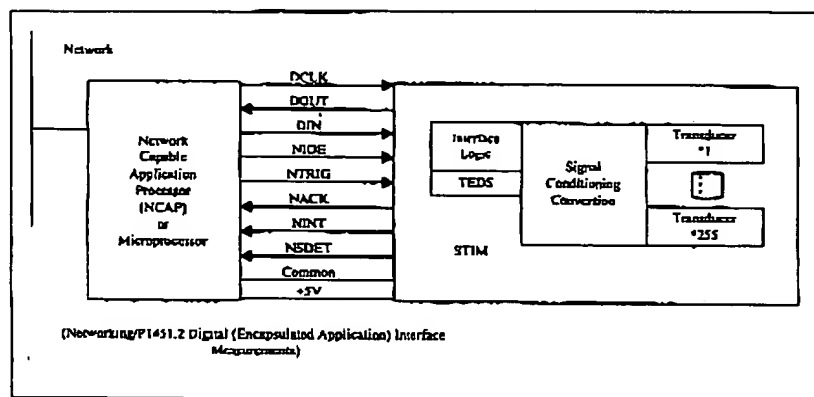
with NCAP. The TEDS is a small physical memory containing manufacturer's information and data for the transducer in a standardized data format. The TII, a 10-wire digital interface with provision for hot-swapping a sensor to a network, is used to access the TEDS, read sensors, and set actuators.

Figure 7-47(a) depicts a STIM and the associated digital interface as described in the P1451.2-1997 hot swap. The STIM shown here is under the control of a network-node microprocessor. In addition to their use in control networks, STIMs can be used with microprocessors in a variety of applications, such as portable instruments and data acquisition cards, as shown in Figure 7-47(b).

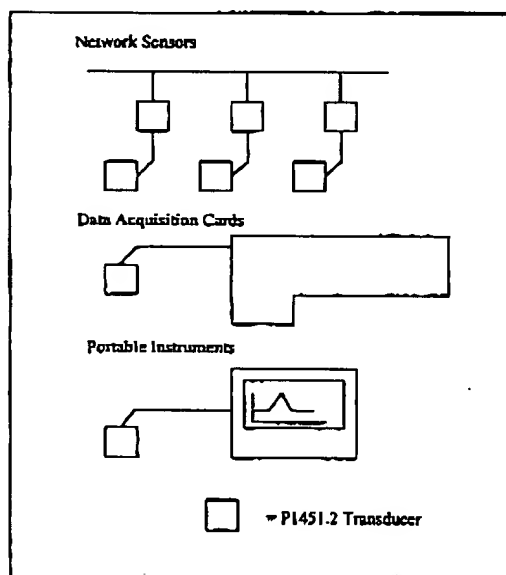
**TABLE 7-5** The ten lines that make up the transducer-independent interface (Courtesy of NIST)

Line	Driven by	Function
DIN	NCAP	Address and data transport from NCAP to STIM
DOUT	STIM	Data transport from STIM to NCAP
DCLK	NCAP	Positive-going edge launches data on both DIN and DOUT
NIOE	NCAP	Signals that the data transport is active and delimits data transport framing
NTRIG	NCAP	Performs triggering function
NACK	STIM	Serves two functions: trigger acknowledge and data transport acknowledge
NINT	STIM	Used by the STIM to request service from the NCAP
NSDET	STIM	Grounded in the STIM and used by the NCAP to detect the presence of a STIM
POWER	NCAP	Nominal 5 V power supply
COMMON	NCAP	Signal common or ground

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(a)



(b)

**FIGURE 7-47** (a) Hardware partition proposed by P1451.2 and (b) possible use for the interface. (Source: Woods, 1996.)

The origin and function of each signal line of the ten-wire interface is listed in Table 7-5.

1451.2 was adopted by the IEEE as a full use standard, designated as IEEE Std. 1451.2-1997. The IEEE Std. 1451.2-1997 can be applied standalone, or it can be used with P1451.1. The two documents together will define a standard interface

for networked smart sensors and actuators to be implemented in a sensor control or actuator control.

The IEEE Std. 1451.2-1997 standard can be ordered from the IEEE customer service (IEEE) in the United States and Canada, or by faxing

### 7.10 P1451 and Practical Considerations

Existing microcontrollers fall short in silicon, either because of functionality or because of standard transducer interface module (STIM) integration. The sensor interface electronics, signal conditioning, linearization, basic communication capabilities, and some microcontrollers with integrated STIM elements can implement most of the functions in conversion speed and accuracy. More economically integrated analog conversion modules are available because of the additional process complexity.

These limitations are overcome by the AduC812 MicroConverter™ (Linear Technology). It integrates key STIM elements with 12-bit ADCs for high-accuracy, fast-conversion-time applications such as pressure and temperature management. In a typical application, the AduC812 conditions signals from various types of sensors, sends signals to actuators, and communicates with the host microprocessor over a serial interface.

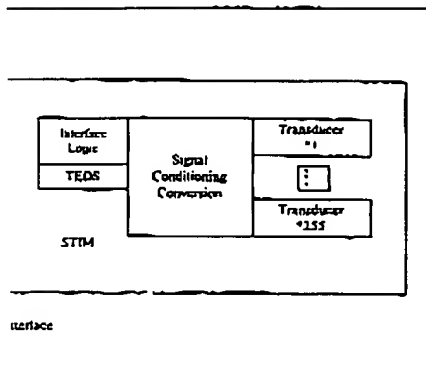
The AduC812 MicroConverter™ includes documentation, applications software, and hardware. Provided on a 3.5-inch floppy disk are an assembler, simulator, debugger, serial driver, and a host interface.

### References

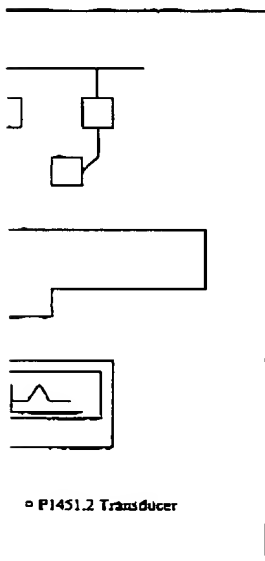
- Ajluni, C. "Pressure Sensors Strive to Stay on Top." Analog Devices, Inc. *Design In Reference Manual*. Analog Devices, Inc. "Data Sheet: Serial Output Transducers." Analog Devices, Inc., MA, USA 1995a.
- Analog Devices, Inc. "Data Sheet: Airflow and Temperature Sensors." Analog Devices, Inc., MA, USA 1995b.
- Analog Devices, Inc. "Data Sheet: Low Voltage Temperature Sensors." Analog Devices, Inc., MA, USA 1996a.
- Analog Devices, Inc. "Data Sheet: ADXL 50." rev. 0. Analog Devices, Inc. "Accuracies of AD 590." Analog Devices, Inc. Applications Reference Manual 1993, pp. 19-3 to 20-3. Analog Devices, Inc. "Practical Design Techniques for Sensors." Analog Devices, Inc., USA 1999.



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(a)



b)

proposed by P1451.2 and (b) possible use for

d) line of the ten-wire interface is listed

s a full use standard, designated as IEEE  
-1997 can be applied standalone, or it can  
is together will define a standard interface

## Sensors 335

for networked smart sensors and actuators. Likewise, the P1451.1 information can be implemented in a sensor control or field network without 1451.2.

The IEEE Std. 1451.2-1997 standard and IEEE P1451.1 D2.2 draft can be ordered from the IEEE customer service department by calling 1-(800)-678-4333 (IEEE) in the United States and Canada, 1-(732)-981-0600 from outside the United States and Canada, or by faxing 1-(732)-981-9667.

### 7.10 P1451 and Practical Components

Existing microcontrollers fall short of fully implementing the standard in silicon, either because of functionality or prohibitive cost. For example, the standard transducer interface module (STIM) portion of the standard specifies the sensor interface electronics, signal conditioning, data conversion, calibration, linearization, basic communication capability, and a non-volatile 565-byte TEDS. Some microcontrollers with integrated 8- or 10-bit ADCs or comparator-based slope conversion can implement most of the STIM functionality, but are limited in conversion speed and accuracy. Moreover, few available controllers have economically integrated analog conversion together with high-density EEPROM because of the additional process complexity requirements of both functions.

These limitations are overcome by recently introduced components such as the AduC812 MicroConverter™ (Leonard, 1998) from Analog Devices, which integrates key STIM elements with 12-bit, 5  $\mu$ s data conversion on a single chip for high-accuracy, fast-conversion-time applications such as battery monitoring, pressure and temperature management, gas monitoring, and leak detection. In a typical application, the AduC812 conditions and converts signals from various types of sensors, sends signals to actuators and display devices, and communicates with the host microprocessor over signal and control lines.

The AduC812 MicroConverter™ is supported by a development system that includes documentation, applications board, power supply, serial port cable, and software. Provided on a 3.5-inch floppy disk, the software consists of an assembler, simulator, debugger, serial downloader, and example code.

### References

- Ajluni, C. "Pressure Sensors Strive to Stay on Top." *Electronic Design* (October 3, 1994), pp. 67-74.
- Analog Devices, Inc. *Design In Reference Manual*. Analog Devices Inc., USA, 1994.
- Analog Devices, Inc. "Data Sheet: Serial Output Thermometers—TMP03/04," rev. 0, Analog Devices, Inc., MA, USA 1995a.
- Analog Devices, Inc. "Data Sheet: Airflow and Temperature Sensor—TMP 12," rev. 0, Analog Devices, Inc., MA, USA 1995b.
- Analog Devices, Inc. "Data Sheet: Low Voltage Temperature Sensors—TMP 35/TMP 36/TMP 37," rev. 0, MA, USA 1996a.
- Analog Devices, Inc. "Data Sheet: ADXL 50," rev. B, Analog Devices, Inc., MA, USA 1996b.
- Analog Devices, Inc. "Accuracies of AD 590," Application note AN-272, Analog Devices, Inc., Applications Reference Manual 1993, pp. 19-3 to 19-6.
- Analog Devices, Inc. "Practical Design Techniques for Sensor Signal Conditioning," Analog Devices Inc., USA 1999.

### 336 Modern Component Families and Circuit Block Design

- Analog Devices, Inc. "Accelerometer Application Guide" (G 2112A). Analog Devices, Inc.
- Bry Zek, J. "Characterization of MEMS Industry in Silicon Valley and Its Impact on Sensor Technology." Proceedings of Sensors Expo, October 1996, pp. 1-13.
- Burri, M. "Calibration Free Pressure Sensor System." Application note AN-1097. Motorola Inc. Sensor Device Data, DL200/D, Rev. 2, 1995, pp. 4-19 to 4-23.
- Caristi, A. J. "A Digital Pressure Gauge Using the Motorola MPX700 Series Differential Pressure Sensors." Application note AN-1105. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-27 to 4-31, 1995.
- Dallas Semiconductor. *System Extension Data Book*. Dallas Semiconductor, TX, 1994-1995.
- Demington, C. "Compensating for Non-Linearity in the MPX10 Series Pressure Transducer." Application note AN 935. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, 1995, pp. 4-4 to 4-10.
- FiS Inc. *SB Products Review: Sensors and Systems Technology*. Japan: FiS Inc., 1996.
- Freeman, W. "Solid State Temperature Sensors Protect and Control." PCIM (November 1993), pp. 39-45.
- Guckel, H. "Micromechanisms Fabrication: Challenge in Micromechanisms and Microelectricity." ISSCC Proceedings, 1992 (IEEE Catalog Number 92CH3128-6), pp. 14-17.
- Hauptmann, P. *Sensors—Principals and Applications*. Englewood Cliffs, NJ: Prentice-Hall, 1991.
- IC Sensors. "Temperature Compensation—IC Pressure Sensors." Application note TN-002. IC Sensors, March 1985.
- IC Sensors. "Signal Conditioning for IC Pressure Sensors." Application note TN-001. IC Sensors, April 1988.
- IC Sensors. "Model 3255 Accelerometer." Application note TN-010. IC Sensors, April 1995.
- IC Sensors. "Understanding Accelerometer Technology." Application note UATRO-9111. IC Sensors, Milpitas, CA, USA.
- Jacobson, E. "Designing Amplifiers for Sensor Applications: A Cookbook Approach." *EDN* (January 4, 1996), pp. 119-128.
- Jacobson, E., and J. Baum. "Optimize Sensor Systems Using Fixed Components." *EDN* (July 6, 1995), pp. 85-95.
- Jacobson, E., and J. Baum. "The A-B-C's of Signal Conditioning Amplifier Design for Sensor Applications." Application note AN 1525. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-152 to 4-158, 1995.
- Klonowski, P. "Use of the AD 590 Temperature Transducer in a Remote Sensing Application." Application note AN-273. Analog Devices, Inc., MA, USA.
- Leonard, M. "Self-Programming Microcontroller Networks Sensors & Transducers." *Electronic Design* (February 9, 1998), pp. 92-94.
- Le Fort, B., and B. Ries. "Taking the Uncertainty out of Thermocouple Temperature Measurement (with AD594/AD595)." Application note AN-274. Analog Devices, Inc., Norwood, MA, USA.
- Lucus, B. "An Evaluation System for Direct Interface of MPX5100 Pressure Sensor with a Microprocessor." Application note AN 1305. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-42 to 4-57, 1995.
- Marcin, J. "Thermocouple Signal Conditioning Using the AD594/AD595." Application note AN-369. Analog Devices, Inc., Norwood, MA, USA.
- Microswitch. "Pressure, Force and Airflow Sensors." In *Catalog 15*. Microswitch, August 1996, pp. 74-91.
- Microswitch. "Temperature and Moisture Sensors." Microswitch, May 1997.
- Microswitch. "Moisture Tutorial-Relative Humidity Sensors." In *Temperature and Moisture Sensors Catalog*. Microswitch, May 1997, pp. B1-B7.
- Motorola Inc. "Analog to Digital Converter Resolution Extension Using a Motorola Pressure Sensor." Application note AN 1100. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-24 to 4-26, 1995.
- Motorola Inc. "Sensor Device Data Book." DL 200/D, Rev. 2, Q2/95. Motorola Inc., 1995.
- Quinnell, R. A. "Silicon Accelerometers Tackle Cost-Sensitive Applications." *EDN* (September 3, 1992), pp. 69-76.
- Schultz, W. "Interfacing Semiconductor Pressure Sensors to Microcomputers." Application note AN-1318. Motorola Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-99 to 4-108, 1995.
- Steele, J. "Get Maximum Accuracy from Temperature Sensors." *Electronic Design* (August 19, 1996), pp. 99-110.
- Swager, A. W. "Hall Effect Sensors-Improved ICs Find Broad Application." *EDN* (May 11, 1989), pp. 75-92.

- Swartz, C., C. Derrington, and J. Gragg. "Temperature-Dependent Pressure Sensor Element." Motorola, AZ, USA.
- Travis, B. "Smart-Sensor Standard Will Ease Net." *Electronic Design* (August 19, 1996), pp. 38-48.
- Travis, B. "Temperature-Management ICs Combat." *Electronic Design* (August 19, 1996), pp. 38-48.
- Walters, D. "Chemical Sensing: An Emergent Market." *Electronic Design* (October 1996), pp. 173-186.
- Winkler, C., and J. Baum. "Barometric Pressure Sensors." Application note AN-1326. Motorola Inc., Norwood, MA, USA.
- Wood, T. "The Hall Effect Sensor." *Sensors* (May 1996), pp. 25-46.
- Woods, S. P. "IEEE-P 1451.2 Smart Interface Module." Helmers Publishing Inc., pp. 25-46.

## and Circuit Block Design

## Sensors 337

on Guide" (G 2112A). Analog Devices, Inc.  
 ty in Silicon Valley and Its Impact on Sensor Tech-  
 ber 1996, pp. 1-13.  
 system." Application note AN-1097. Motorola Inc.,  
 , pp. 4-19 to 4-23.  
 the Motorola MPX700 Series Differential Pressure  
 a Inc., Sensor Device Data, DL200/D, Rev. 2, pp. 4-

ook. Dallas Semiconductor, TX, 1994-1995.  
 y in the MPX10 Series Pressure Transducer." Appli-  
 Device Data, DL200/D, Rev. 2, 1995, pp. 4-4 to

ms Technology. Japan: FiS Inc., 1996.  
 s Protect and Control." PCIM (November 1993),

allenge in Micromechanisms and Microelectricity."  
 mber 92CH3128-6), pp. 14-17.  
 ations. Englewood Cliffs, NJ: Prentice-Hall, 1991.  
 Pressure Sensors." Application note TN-002. IC

re Sensors." Application note TN-001. IC Sensors,

ication note TN-010. IC Sensors, April 1995.  
 ology." Application note UATRO-9111. IC Sensors.

, applications: A Cookbook Approach." *EDN* (January

Systems Using Fixed Components." *EDN* (July 6,

Signal Conditioning Amplifier Design for Sensor  
 Motorola Inc., Sensor Device Data, DL200/D, Rev. 2,

re Transducer in a Remote Sensing Application."  
 ic., MA, USA.  
 r Networks Sensors & Transducers." *Electronic De-*

ity out of Thermocouple Temperature Measurement  
 -274, Analog Devices, Inc., Norwood, MA, USA.  
 erface of MPX5100 Pressure Sensor with a Micro-  
 Motorola Inc., Sensor Device Data, DL200/D, Rev. 2,

Using the AD594/AD595." Application note AN-369.

sors." In *Catalog 15*. Microswitch, August 1996,

rs." Microswitch, May 1997.  
 dity Sensors." In *Temperature and Moisture Sensors*  
 1.

lution Extension Using a Motorola Pressure Sensor."  
 sor Device Data, DL200/D, Rev. 2, pp. 4-24 to 4-26,

200/D, Rev. 2, Q2/95. Motorola Inc., 1995.  
 Cost-Sensitive Applications." *EDN* (September 3,

: Sensors to Microcomputers." Application note AN-  
 200/D, Rev. 2, pp. 4-99 to 4-108, 1995.  
 perature Sensors." *Electronic Design* (August 19,

Cs Find Broad Application." *EDN* (May 11, 1989).

Swartz, C., C. Derrington, and J. Gragg. "Temperature Compensation Methods for the Motorola X-ducer Pressure Sensor Element." Motorola Application note AN 840. Motorola Inc., Phoenix, AZ, USA.

Travis, B. "Smart-Sensor Standard Will Ease Networking Woes." *EDN* (June 22, 1995), pp. 49-52.  
 Travis, B. "Temperature-Management ICs Combat System Meltdown." *EDN* (August 15, 1996), pp. 38-48.

Walters, D. "Chemical Sensing: An Emergent MEMS Technology." Proceedings of Sensors Expo, October 1996, pp. 173-186.

Winkler, C., and J. Baum. "Barometric Pressure Measurement Using Semiconductor Pressure Sensors." Application note AN-1326. Motorola Inc.

Wood, T. "The Hall Effect Sensor." *Sensors* (March 1986).

Woods, S. P. "IEEE-P 1451.2 Smart Interface Module." Proceedings of Sensors Expo, October 1996, Helmers Publishing Inc., pp. 25-46.

## CHAPTER 8

# Nonlinear Devices

## 8.1 Introduction

By exploiting the basic physics of semiconductor devices it is possible to design circuits that perform a wide variety of mathematical operations, including addition, subtraction, multiplication, and division as well as trigonometric, logarithmic, and exponential functions. Such circuits perform in the analog domain and frequently offer real advantages over more conventional digital computation. Operations where analog computation is preferable to digital include those where both the input and output signals must be analog, limited amounts of processing are required and no digital circuitry is present, the signal is differentiated to produce a rate signal, fast signals must be processed in real time, large dynamic ranges are involved, and complex or transcendental functions must be evaluated.

In an electronic design world, where a digital approach to design is preferred in many instances, much room remains for analog computation techniques, particularly in situations where a wide, dynamic range of signals or fast signals can be processed. To explain this situation, we take the case of a simple AC power meter. A simple AC power meter may be constructed very easily with a single analog multiplier as per Figure 8-1(a), where the moving coil meter can act as the integrator. A digital power meter would require conversion of both voltage and current to digital form, with considerable attention to the timing of the conversions, since the relative phase of the two signals is of critical importance. However, if with the advantage of a CPU (see Figure 8-1(b)) that has a display driven by it and a multiplexed ADC with spare capacity, the power metering facility could be added to the base system at minimal additional cost.

As another example, the first derivative of a varying analog signal is complex to calculate using digital techniques, compared to a simple C-R network for analog differentiation (Analog Devices, 1987, Section 5). Digitizing a signal with wide dynamic range also is expensive (see Figure 8-2). If such a signal is digitized

## 340 Modern Component Families and Circuit Block Design

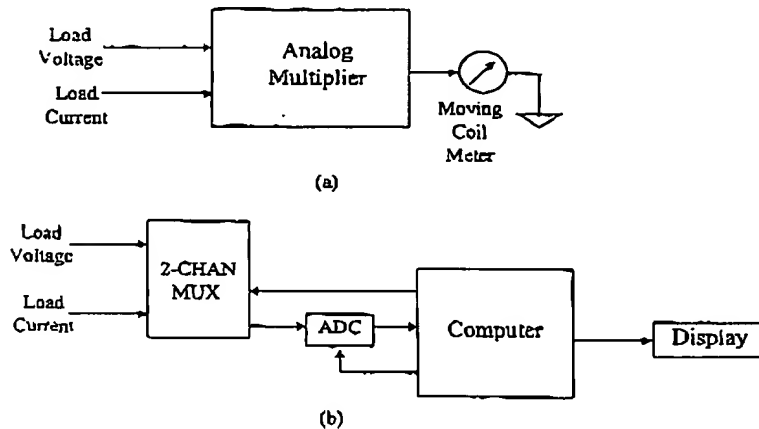


FIGURE 8-1 Power meter implementation: (a) analog approach, (b) digital approach

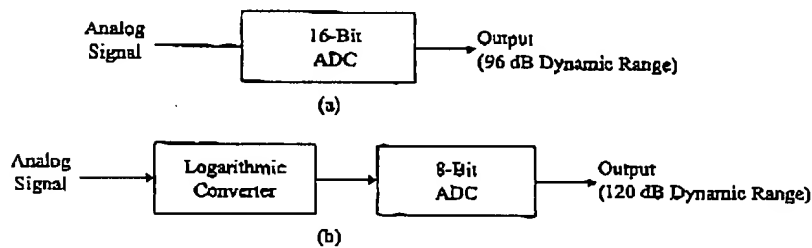


FIGURE 8-2 Analog processing advantage of signals with high dynamic range: (a) a 16-bit ADC, the expensive way, yielding a 96 dB dynamic range; (b) an inexpensive 8-bit ADC with a logarithmic converter, yielding a 120 dB dynamic range

with a 16-bit ADC (a comparatively expensive device), the ratio of an LSB to full scale is 96 dB; whereas if the signal were first applied to a logarithmic converter (frequently misnamed a *logarithmic amplifier*), then a dynamic range approaching 120 dB is practical with an 8-bit ADC.

Historically, analog computers have been slow devices. Even though high-frequency multipliers, modulators, logarithmic amplifiers, and other function generators have been available for many years, they generally have had relatively poor accuracy and stability and have not been considered analog computers. Within the last decade, a few classes of accurate nonlinear devices have entered the market: multipliers, modulators, and log amps (Analog Devices, 1990, Section 5). This chapter is an introduction to modern nonlinear devices, their design concepts, and special application areas.

## 8.2 A Basic Semiconductor to Analog Computation

The operation of many analog arithmetic properties of silicon junctions, voltage relationship

$$I = I_0 \left( e^{\frac{qV}{kT}} - 1 \right)$$

This could be rewritten as

$$V = \frac{kT}{q} \ln \left( \frac{I}{I_0} + 1 \right)$$

where

$I$  = the current through the diode

$k$  = Boltzman's constant (1.38

$V$  = the voltage across the diode

$q$  = a constant equal to unit charge

$T$  = the absolute temperature in Kelvin

$I_0$  = the extrapolated current for zero voltage

Referring to Figure 8-3, these equations show that the diode current increases exponentially with voltage.

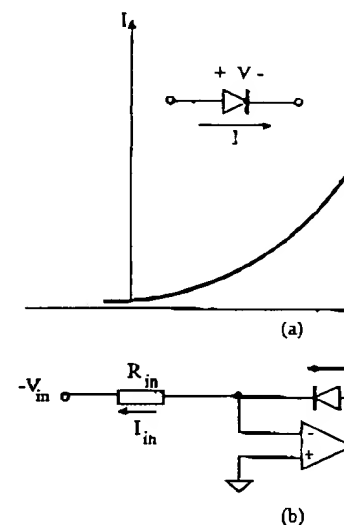
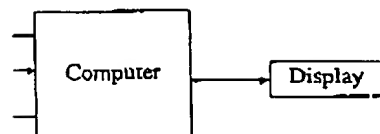
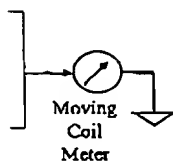


FIGURE 8-3 (a) Diode curve, (b) diode circuit

## Circuit Block Design



in: (a) analog approach, (b) digital approach

Output  
(96 dB Dynamic Range)

8-Bit ADC  
Output  
(120 dB Dynamic Range)

ge of signals with high dynamic range: (a)  
a 96 dB dynamic range; (b) an inexpensive  
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## Nonlinear Devices 341

## 8.2 A Basic Semiconductor Physics-Based Approach to Analog Computation Circuits

The operation of many analog computational circuits depends on the logarithmic properties of silicon junctions. An ideal logarithmic diode has the current voltage relationship

$$I = I_0(e^{qV/kT} - 1) \quad (8.1)$$

This could be rewritten as

$$V = \frac{kT}{q} \ln \left( \frac{I}{I_0} + 1 \right) \approx \frac{kT}{q} \ln \left( \frac{I}{I_0} \right) \quad (8.2)$$

where

$I$  = the current through the diode;

$k$  = Boltzman's constant ( $1.38062 \times 10^{-23}$ );

$V$  = the voltage across the diode;

$q$  = a constant equal to unit charge,  $1.60219 \times 10^{-19}$  coulombs;

$T$  = the absolute temperature in Kelvin;

$I_0$  = the extrapolated current for  $E_0 = V = 0$  volts.

Referring to Figure 8-3, these equations clearly show that the current in a diode increases exponentially with voltage or, conversely, the voltage increases

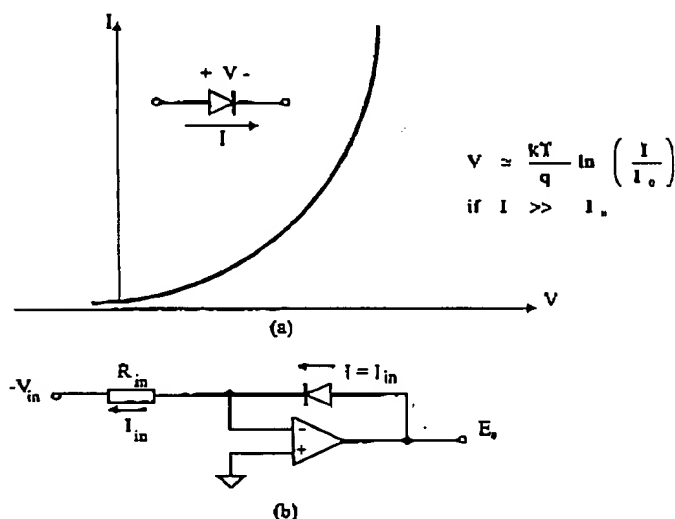


FIGURE 8-3 (a) Diode curve, (b) diode log converter

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logarithmically with current. These equations are less clear in showing that  $I_0$ , the theoretical diode current at zero voltage, is temperature dependent and so the variation of a diode's behavior with temperature is by no means as simple as the equation would suggest; that is, the voltage is not proportional to absolute temperature at a fixed current. Several approximations concerning the logarithmic behavior of diodes are worth remembering:

$$\frac{kT}{q} = 26 \text{ mV (at } 28.58^\circ\text{C)} \quad (8.3)$$

$$\frac{kT}{q} \ln 10 = 60 \text{ mV (at } 29.25^\circ\text{C)} \quad (8.4)$$

These approximations simplify the diode expression to

$$V = 60 \text{ mV} \log \frac{I}{I_0} \quad (8.5)$$

This simply says that  $V$  increases by 60 mV every time the current increases by a factor of 10 at  $29.25^\circ\text{C}$ .

If we were to place an ideal logarithmic diode in the feedback path (output to inverting input) of an operational amplifier and apply a current to the inverting input, the output voltage would be the logarithm of the input current times a temperature varying constant. For the circuit in Figure 8-3(b), if  $I_{in} \gg I_0$ ,

$$E_0 = \frac{kT}{q} \ln \left( \frac{I_{in}}{I_0} \right) \approx 0.06 \log \frac{V_{in}}{R_{in} I_0} \quad (8.6)$$

It is unfortunate that real diodes are not ideal logarithmic diodes. In a real diode, the bulk resistivity,  $R_B$ , of the silicon limits the logarithmic accuracy at high currents and diffusion currents in surface inversion layers and generation-recombination effects in space-charge regions cause a scale factor error,  $m$ , at low currents. We therefore find that

$$E_0 = m \frac{kT}{q} \ln \left( \frac{I}{I_0} \right) + I_{RB} \quad (8.7)$$

where  $m$  varies with the current.

Even with similar diodes,  $m$  can vary (it is never less than 1 and may be as high as 4), as does the value of  $E_0$  at which  $m$  changes. General purpose diodes therefore are impractical as logarithmic diodes for dynamic ranges of more than 100:1 (two decades).

Luckily, we can replace the diode with a grounded-base transistor as per Figure 8-4 and get a dynamic range of 1 million:1 (six decades) or more—the only disadvantage of such a circuit is that the signals can have only a single polarity.

From the Ebers and Moll equations (see Sheingold, 1976, for a detailed derivation), it may be shown that

$$E_0 = \frac{kT}{q} \ln \left( \frac{I_{in}}{I_{ES}} \right) - \frac{kT}{q} \ln \alpha_n \quad (8.8)$$

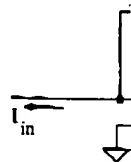


FIGURE 8-4 Transistor log converter

where  $I_{in} \gg I_{ES}$ ;  $I_{ES}$  is the emitter current-transfer ratio ( $\alpha_n$  is not the gr

Since  $I_{ES}$  is less than a picoamp range of currents, in the silicon planar converters, the effect of the second equation simplifies to

$$E_0 = \frac{kT}{q}$$

Such logarithmic converters are  $kT/q$  has a temperature coefficient of 0 every  $10^\circ\text{C}$  temperature rise and varies these basic concepts, in refined forms circuits, are used in nonlinear circuits. techniques, see Analog Devices, Inc.,

## 8.3 Important Design Considerations

In the discussion of nonlinear devices are the dynamic range of a signal and

### 8.3.1 Dynamic Range

In many cases, a wide dynamic range something to be preserved at all costs. quality reproduction of music and communication signal must be compressed to a smaller range. Compression is used in magnetic tape recording; the dynamic range is limited by tape saturation. In professional audio, the "undo" by precisely matched nonlinear techniques are used in conveying speech. The reciprocal processes of compression and expansion are more likely to be measured in fidelity. The reciprocal processes of com





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using "compandors," and many schemes have been devised to achieve this function. In terms of the signal voltage,

$$\text{Dynamic range (dB)} = 20 \log_{10} \frac{\text{Largest signal voltage}}{\text{Smallest signal voltage}} \quad (8.10)$$

Note that in a linear-impedance system, the power is proportional to the signal voltage (or current) squared. Accordingly,

$$\text{Dynamic range (dB)} = 10 \log_{10} \frac{\text{Largest signal power}}{\text{Smallest signal power}} \quad (8.11)$$

Also, it is useful to differentiate between the dynamic range of the signal and that of the processing system. The signal dynamic range is

$$\text{Signal dynamic range} = 20 \log_{10} \frac{\text{Largest actual signal voltage}}{\text{Smallest actual signal voltage}} \quad (8.12)$$

whereas the system dynamic range is

$$\text{System dynamic range} = 20 \log_{10} \frac{\text{Largest permissible signal voltage}}{\text{Smallest detected signal voltage}} \quad (8.13)$$

In system design, one should be concerned with the system's dynamic range, which should match or exceed the signal dynamic range.

#### 8.3.2 Noise Limitations

The dynamic range of all signal-processing systems is limited by random noise, which sets a fundamental bound on the smallest signal that can be detected or otherwise utilized with an adequate signal-to-noise ratio (SNR). This noise may be generated by numerous mechanisms, including those associated with the source itself (e.g., antenna, photomultiplier, piezoelectric transducer) as well as by the active and passive devices in the amplifiers.

Noise cannot be discussed without reference to bandwidth, which will be unavoidably limited by the types of amplifier used. Deliberate filtering often is included in a signal-processing channel to reduce noise, as well as to improve the separation of wanted from unwanted signals. This may take the form of bandpass, low-pass, or high-pass functions or combinations of these, depending on the situation. Nonlinear filtering also may be used, for example, to minimize the disturbance of the signal path in the presence of impulsive noise.

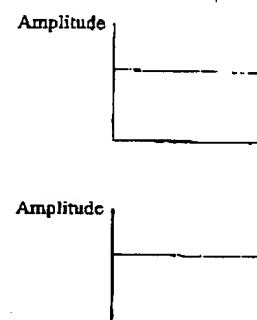
The noise powers of uncorrelated sources add up, so noise voltages (or currents) must be added using a root-sum-of-squares (RSS) calculation. This leads to some rather startling consequences. Suppose a system has a major voltage noise source of magnitude  $E_a$  and several minor noise sources whose RSS sum to a magnitude of  $E_b$ . Then,  $E_a$  needs to be only twice  $E_b$  for the major source to contribute almost 90% of the total system noise. When  $E_a/E_b = 5$ , 98% of the noise is due to  $E_a$ .

It follows that the overall noise greatly by (i) minimizing the input to the highest possible gain in this stage. This frequently cannot be realized in systems with a large dynamic range, because the high gain is required at maximum signal levels.

Noise frequently is specified in terms of noise bandwidth. The term reflects the fact that the noise power in the system's noise bandwidth,  $B_N$ , is equal to the noise power in the system's noise bandwidth,  $B_N$ , if the system's noise bandwidth is not equal to the bandwidth of an equivalent system at that frequency. A system with a noise bandwidth  $B_N$  has a  $B_N$  value equal to  $\pi f_0/2$ , or  $\pi f_0/4$  for both voltage and current components. For pass sections in cascade,  $B_N$  is  $\pi f_0/4$  for both voltage and current components. The square of either the voltage or current component has dimensions of volts<sup>2</sup>/Hz and amps<sup>2</sup>/Hz.

Noise signals usually are small and negligible. In such circumstances, it is not necessary to evaluate each contributing source individually to calculate the total noise. A notable exception is where even very small noise voltage sources in later stages in the amplifier. Special care must be taken where even very small noise voltage sources in later stages in the amplifier. Special care must be taken where even very small noise voltage sources in later stages in the amplifier.

For details on noise performance, see Section 2.3.2 of Chapter 2. While noise is small, performance at the upper end of the dynamic range, performance at the upper end of the dynamic range, importance of nonlinear aspects of circuit design.



**FIGURE 8-5** Filter noise bandwidths: (a) single-pole low-pass filter, (b) two-pole low-pass filter.

## Circuit Block Design

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have been devised to achieve this func-

$$\frac{\text{Largest signal voltage}}{\text{Smallest signal voltage}} \quad (8.10)$$

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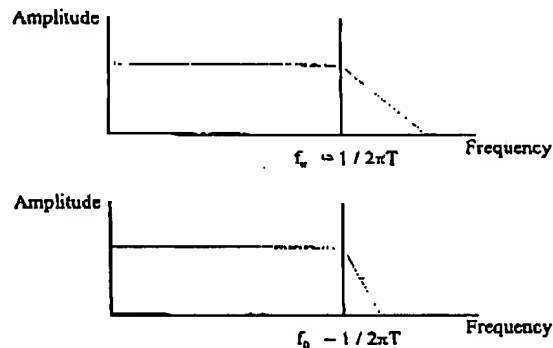
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ystem noise. When  $E_a/E_b = 5$ , 98% of

It follows that the overall noise performance of a practical system can benefit greatly by (i) minimizing the input-referred noise of the first stage and (ii) using the highest possible gain in this stage. However, the second of these objectives frequently cannot be realized in systems that must handle signals of a large dynamic range, because the high gain would preclude distortion-free operation at maximum signal levels.

Noise frequently is specified in terms of a noise spectral density (NSD). The term reflects the fact that the total noise power is directly proportional to the system's noise bandwidth,  $B_N$  (in Hertz). The NSD therefore usually is of interest in specifying a channel's input-noise limitations. Note that, in general, the noise bandwidth is not equal to the  $-3\text{dB}$  bandwidth.  $B_N$  can be viewed as the bandwidth of an equivalent system with a "brick-wall" cessation of response at that frequency. A system with a single-pole low-pass corner at  $f_0 = 1/2\pi T$  has a  $B_N$  value equal to  $\pi f_0/2$ , or  $1.57f_0$ , while for two such real pole low-pass sections in cascade,  $B_N$  is  $\pi f_0/4$  (see Figure 8-5). The total NSD will have both voltage and current components. Since the noise power is proportional to the square of either the voltage or current, these two noise components have the dimensions of volts/ $\sqrt{\text{Hz}}$  and amps/ $\sqrt{\text{Hz}}$ .

Noise signals usually are small, and therefore nonlinear effects often are negligible. In such circumstances, it is permissible to use superposition methods to evaluate each contributing source independently, followed by an RSS calculation to calculate the total noise. A notable exception is the logarithmic amplifier, where even very small noise voltages at the input can cause heavy limiting in later stages in the amplifier. Special approaches to both noise analysis and noise specification are required in such cases.

For details on noise performance, see Analog Devices, Inc. (1992a) and Section 2.3.2 of Chapter 2. While noise limits the low end of a system's dynamic range, performance at the upper end of signal range is degraded by the increasing importance of nonlinear aspects of circuit behavior.



**FIGURE 8-5** Filter noise bandwidths: (a) single-pole low-pass filter ( $B_N = \pi f_0/2 = 1.57f_0$ ), (b) two single-pole low-pass filters sections in cascade ( $B_N = \pi f_0/4$ )

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## 8.4 Logarithmic Converters

The conversion of a signal to its equivalent logarithmic value involves a nonlinear operation, the consequences of which can be confusing if not fully understood. It is important to realize that many of the familiar concepts of linear circuits are irrelevant to log amps. For example, the incremental gain of an ideal log amp approaches infinity as the input tends to 0, and change of offset at the output of a log amp is equivalent to a change of amplitude at its input, not a change of input offset. The commonly used term *logarithmic amplifier* is something of a misnomer but is used lavishly.

If we consider the equation  $y = \log(x)$ , as shown in Figure 8-6(a), every time  $x$  is multiplied by a constant  $A$ ,  $y$  increases by another constant  $A_1$ . Thus, if  $\log(K) = K_1$ , then  $\log(AK) = K_1 + A_1$ ;  $\log(A^2K) = K_1 + 2A_1$ ;  $\log(K/A) = K_1 - A_1$ . As shown in figure 8.6(a) when  $x$  is 1,  $y$  approaches 0.

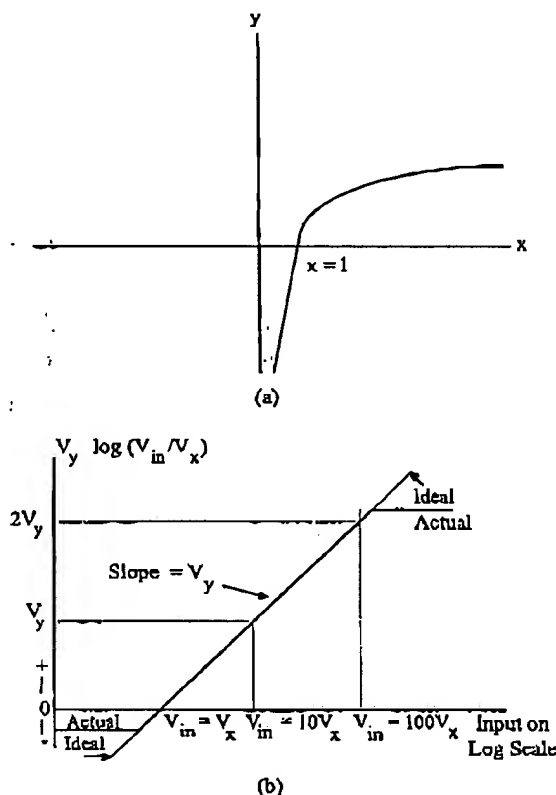


FIGURE 8-6 (a) Graph of  $y = \log(x)$ , (b) log amp transfer function

A practical log amp has the Figure 8-6(b). Such a practical log a

$$V_{out} = 1$$

This is valid over some range of (40 dB) to over 1 million:1 (120 dB) is logarithmic, and the ideal transfer  $V_x$ , the logarithm is 0 ( $\log 1 = 0$ ).  $V_y$  of the log amp, because the graph cre

With inputs very close to 0, log most then follow a linear  $V_{in}/V_{out}$  noise. Noise often limits the dynamic the dimensions of voltage, because divided by a voltage,  $V_x$ , because the dimensionless ratio.

## 8.4.1 Practical Log Amps

The logarithm function is indeter can respond to negative inputs in thr

1. They can give a full-scale negative basic log amp saturates with negative
2. They can give an output proportional input and disregard its sign, as she can be considered a full-wave detector often is referred to as a *detecting*
3. They can give an output proportional input and have the same sign as the of log amp can be considered a *vi* and may be known as a *logarithmic* a *true log amp*.

## 8.4.2 Practical Implementations

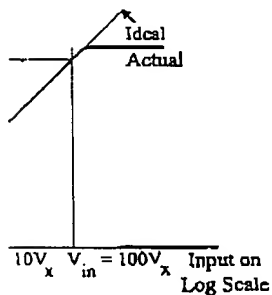
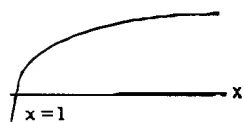
Three basic architectures are used Inc.: the basic diode log amp, the true amp.

## 8.4.2.1 The Basic Diode Log

As per the discussion in Section 1 amp function (see Figure 8-3). In practice is limited to 40–60 dB because of non- if the diode is replaced with a diode co the dynamic range can be extended to

equivalent logarithmic value involves a  $f$  which can be confusing if not fully many of the familiar concepts of linear ample, the incremental gain of an ideal it tends to 0, and change of offset at to a change of amplitude at its input, only used term *logarithmic amplifier* is ishly.

$g(x)$ , as shown in Figure 8-6(a), every ncreases by another constant  $A_1$ . Thus,  $1$ ;  $\log(A^2K) = K_1 + 2A_1$ ;  $\log(K/A) = 1$   $x$  is 1,  $y$  approaches 0.



log amp transfer function

A practical log amp has the graph of transfer characteristics shown in Figure 8-6(b). Such a practical log amp has the transfer function

$$V_{out} = V_y \log_{10} \left( \frac{V_{in}}{V_x} \right) \quad (8.14)$$

This is valid over some range of input values, which may vary from 100:1 (40 dB) to over 1 million:1 (120 dB). The scale of the horizontal axis (the input) is logarithmic, and the ideal transfer characteristic is a straight line. When  $V_{in} = V_x$ , the logarithm is 0 ( $\log 1 = 0$ ).  $V_x$  therefore is known as the *intercept voltage* of the log amp, because the graph crosses the horizontal axis at this value of  $V_{in}$ .

With inputs very close to 0, log amps cease to behave logarithmically and most then follow a linear  $V_{in}/V_{out}$  law. This behavior often is lost in device noise. Noise often limits the dynamic range of a log amp. The constant  $V_y$  has the dimensions of voltage, because the output is a voltage. The input,  $V_{in}$ , is divided by a voltage,  $V_x$ , because the argument of a logarithm must be a simple dimensionless ratio.

#### 8.4.1 Practical Log Amps and Negative Values of $x$

The logarithm function is indeterminate for negative values of  $x$ . Log amps can respond to negative inputs in three different ways:

1. They can give a full-scale negative output as shown in Figure 8-7(a). This basic log amp saturates with negative inputs.
2. They can give an output proportional to the log of the absolute value of the input and disregard its sign, as shown in Figure 8-7(b). This type of log amp can be considered a full-wave detector with a logarithmic characteristic and often is referred to as a *detecting log amp*.
3. They can give an output proportional to the log of the absolute value of the input and have the same sign as the input, as shown in Figure 8-7(c). This type of log amp can be considered a video amp with a logarithmic characteristic and may be known as a *logarithmic video* (log video) *amplifier* or, sometimes, a *true log amp*.

#### 8.4.2 Practical Implementation

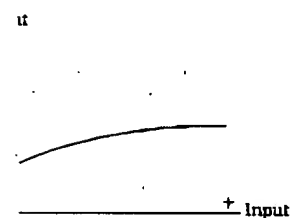
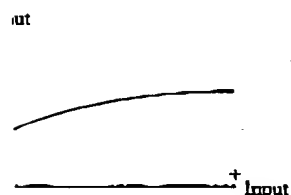
Three basic architectures are used by manufacturers such as Analog Devices, Inc.: the basic diode log amp, the true log amp, and the successive detection log amp.

##### 8.4.2.1 The Basic Diode Log Amp

As per the discussion in Section 8.2, a simple diode could be used for a log amp function (see Figure 8-3). In practice, the dynamic range of this configuration is limited to 40–60 dB because of nonideal characteristics of the diode. However, if the diode is replaced with a diode connected transistor, as shown in Figure 8-4, the dynamic range can be extended to 120 dB or more. This type of log amp has



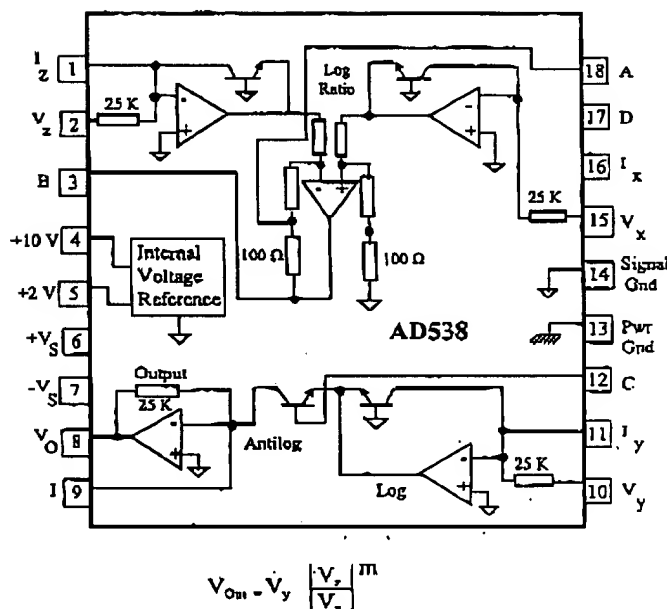
## Circuit Block Design



cs of  $x$  input: (a) basic log amp, (b) detecting log amp

intercept are temperature dependent, its bandwidth is both limited and dependent on the input signal. When log amps are used on a single chip for both log and antilog operations, the intercept is unimportant, since it is compensated

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**FIGURE 8-8** The AD-538 analog computational unit. (Reproduced by permission of Analog Devices, Inc.)

for by a similar variation in the antilogging. An example of a practical device that utilizes such techniques is the AD-538 analog computation unit (ACU) from Analog Devices, Inc. (Figure 8-8). This device, which has a transfer function of  $V_{out} = V_y(V_z/V_x)^m$ , can multiply, divide, and raise to powers. When actual logging is required, these types of devices require temperature compensation (Sheingold, 1976).

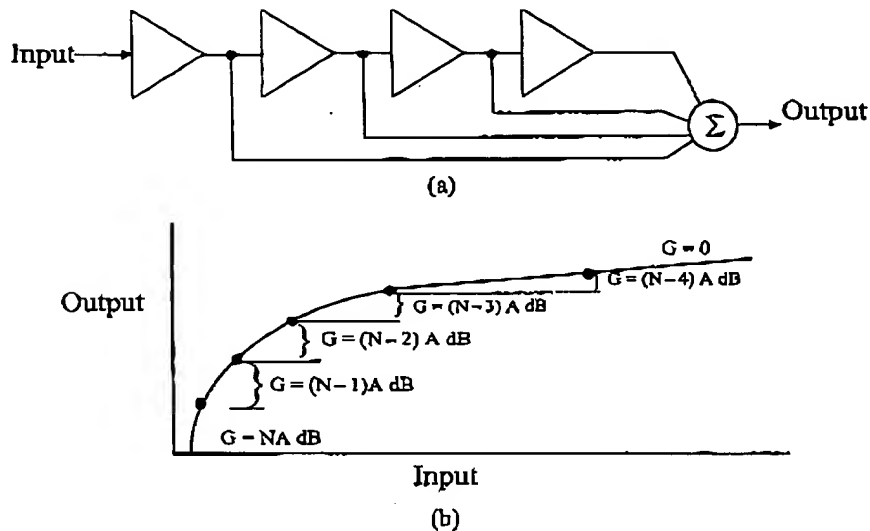
A major disadvantage of this type of log amp for high-frequency applications is its limited frequency response, limited by Miller capacitance or the residual feedback capacitance of these devices (Analog Devices, Inc., 1995). Practical limits are within a few hundred kHz. Therefore, for high-frequency applications detecting and true log architectures are used.

#### 8.4.2.2 True and Detecting Log Amps

Although these two types differ in detail, the general principle behind their design is the same: Instead of one amplifier having a logarithmic characteristic, these designs use a number of similar, cascaded linear stages having well-defined large signal behavior.

As shown in Figure 8-9(a) consider  $N$  cascaded limiting amplifiers, the output of each driving a summing circuit as well as the next stage. If each amplifier has a gain of  $A$  dB, the small signal gain of the strip is  $NA$  dB. If

## 350 Modern Component Families and Circuit Block Design

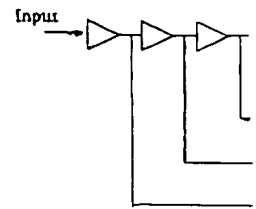


**FIGURE 8-9** Multistage log amp: (a) architecture, (b) response for unipolar case

the input signal is small enough for the last stage not to limit, the output of the summing amplifier will be dominated by the output of the last stage. As the input signal increases, the last stage will limit. It now will make a fixed contribution to the output of the summing amplifier, but the incremental gain to the summing amplifier will drop to  $(N - 1)$  dB. As the input continues to increase, this stage in turn will limit and make a fixed contribution to the output, and the incremental gain will drop to  $(N - 2)$  dB, and so forth, until the first stage limits and the output ceases to change with increasing signal input.

The response curve therefore is a set of straight lines, as shown in Figure 8-9(b). The total of these lines, though, is a very good approximation to a logarithmic curve and, in practice, is an even better one, because few limiting amplifiers, especially high-frequency ones, limit quite as abruptly as this model assumes. Due to the compromise needed between log approximation and number of gain stages, gains of 10–12 dB are chosen in practical devices (Analog Devices, 1995).

This general model, which is ideal, becomes difficult to implement at high frequencies due to delays associated with each stage. If each stage has a delay of  $t$  ns, a signal that passes through all stages will have a delay of  $Nt$  ns compared to a signal that passes only one stage, which is delayed by only  $t$  ns. Some solutions for such difficulties are discussed in Analog Devices (1995). Multistage architectures such as these or their variations are video log amps or true log amps. However, the most common types of high-frequency log amps are the devices based on successive detection architecture.



**FIGURE 8-10** Successive detection in

#### 8.4.2.3 Successive Detectic

The successive detection log are described previously, but instead of switches are applied to detectors, and the detectors are shown in Figure 8-10. If the detectors have cut points, the log will involve no more than connecting all the

Log amps using this architecture and a limiting output. In many applications in some (FM receivers with "S" meter) log output of a successive detection level information, and the phase and frequency

In the past, it has been necessary to use frequency successive detection log amplifiers. These typically are assembled from discrete components. Advances in IC processes have allowed these functions to be integrated on a single chip.

The AD-640 log amp from Anal detection type log amp for high-frequency limiting stages (10 dB per stage) a package, and its logarithmic performance diagram of AD-640 is shown in Figure

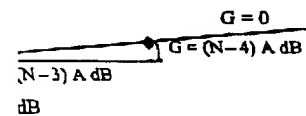
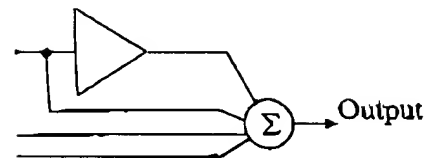
With reference to Figure 8-11(b), a condition where  $V_x$  is calibrated to 1 mV,  $V_y$  is proportional to  $V_x$ . Base 10 logarithmic relationship to decibel values. For  $V_{in}$  so the output voltage is  $V_y$ . At  $V_{in} =$  therefore can be viewed either as the factor.

The AD-640 conforms to equation (1) in the form of current rather than voltage:

$$I_{out} = I_v$$

Each of the five stages in the AD-detected output. The transfer function

## Circuit Block Design



put

architecture, (b) response for unipolar case

last stage not to limit, the output of the the output of the last stage. As the input . It now will make a fixed contribution out the incremental gain to the summing he input continues to increase, this stage bution to the output, and the incremental forth, until the first stage limits and the signal input.

a set of straight lines, as shown in though, is a very good approximation 2, is an even better one, because few uency ones, limit quite as abruptly as nise needed between log approximation -12 dB are chosen in practical devices

becomes difficult to implement at high 1 each stage. If each stage has a delay of es will have a delay of  $Nt$  ns compared which is delayed by only  $t$  ns. Some ed in Analog Devices (1995). Multistage ons are video log amps or true log amps. igh-frequency log amps are the devices re.

## Nonlinear Devices 351

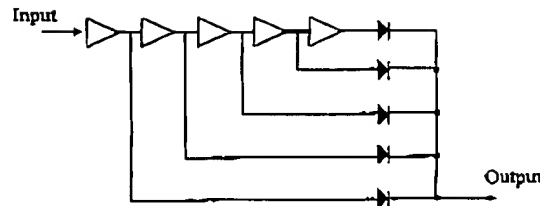


FIGURE 8-10 Successive detection logarithmic amplifier

## 8.4.2.3 Successive Detection Log Amps

The successive detection log amp consists of cascaded limiting stages as described previously, but instead of summing their outputs directly, these outputs are applied to detectors, and the detector outputs are summed as shown in Figure 8-10. If the detectors have current outputs, the summing process may involve no more than connecting all the detector outputs.

Log amps using this architecture have two types of output: the log output and a limiting output. In many applications, the limiting output is not used, but in some (FM receivers with "S" meters, for example) both are necessary. The log output of a successive detection log amplifier generally contains amplitude information, and the phase and frequency information is lost.

In the past, it has been necessary to construct high-performance, high-frequency successive detection log amps using a number of individual limiting amplifiers. These typically are assembled in complex and costly hybrids. Recent advances in IC processes have allowed this complete function to be integrated on a single chip.

The AD-640 log amp from Analog Devices is an example of successive detection type log amp for high-frequency use. The AD-640 log amp contains five limiting stages (10 dB per stage) and five full-wave detectors in a single IC package, and its logarithmic performance extends from DC to 145 MHz. A block diagram of AD-640 is shown in Figure 8-11.

With reference to Figure 8-11(b), the AD-640 has its log amp transfer function where  $V_x$  is calibrated to 1 mV exactly. The slope of the line is directly proportional to  $V_y$ . Base 10 logarithms are used in this context to simplify the relationship to decibel values. For  $V_{in} = 10V_x$ , the logarithm has a value of 1, so the output voltage is  $V_y$ . At  $V_{in} = 100V_x$ , the output is  $2V_y$ , and so on.  $V_y$  therefore can be viewed either as the slope voltage or as the volts per decade factor.

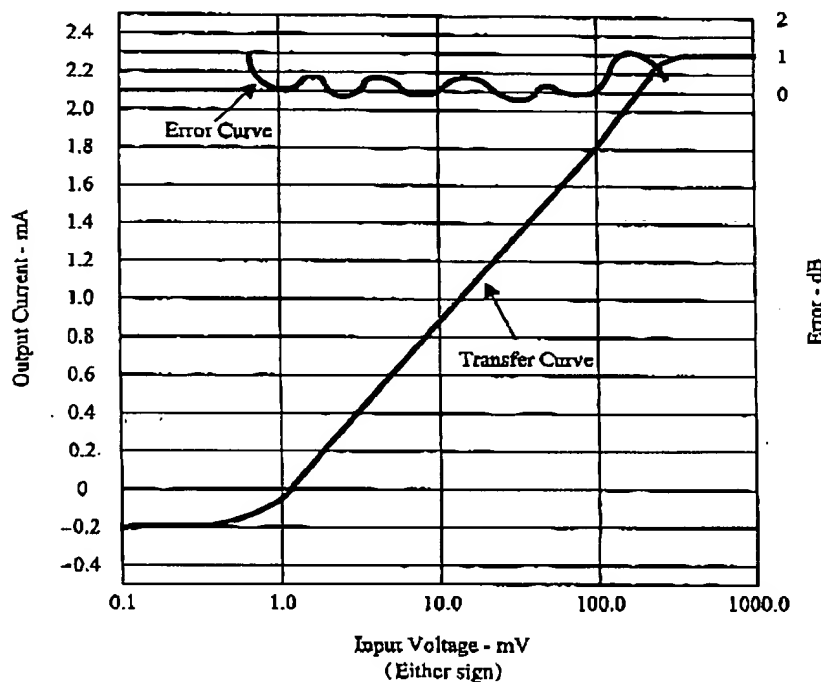
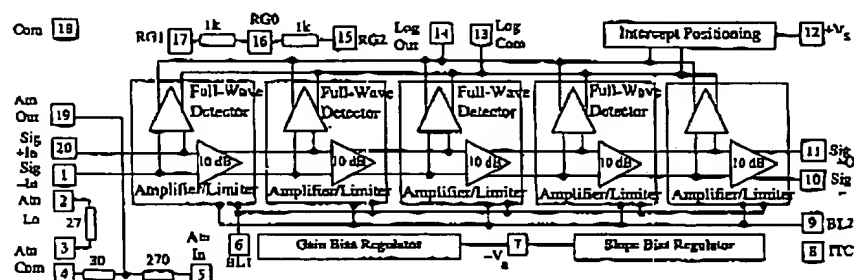
The AD-640 conforms to equation (8.1) except that its two outputs are in the form of current rather than voltage:

$$I_{out} = I_y \log(V_{in}/V_x) \quad (8.15)$$

Each of the five stages in the AD-640 has a gain of 10 dB and a full-wave detected output. The transfer function of the device is shown in Figure 8-11(b)



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**FIGURE 8-11** The AD-640 log amp: (a) block diagram, (b) transfer function and error curve. (Reproduced by permission of Analog Devices, Inc.)

along with the error curve. Note the excellent log linearity over an input range of 1–100 mV (40 dB). Although well suited to RF applications, the AD-640 is DC coupled throughout. This allows it to be used in low-frequency and very low-frequency systems, including audio measurements, sonar, and other instruments requiring operation to low frequencies or even DC. Unlike many other log amps, the AD-640 is laser trimmed to a high absolute accuracy of both slope and intercept and is fully temperature compensated. Some key features of the AD-640 are

1. 45 dB dynamic range; two can cas
2. Bandwidth DC to 145 MHz (120 l
3. Slope of 1 mA/decade, temperatur
4. Less than 1 dB log nonlinearity.
5. Balanced circuitry for stability and

For further details on applications

## 8.4.3 Key Parameters of L

In selecting log amps for a given ered are listed in Table 8-1.

Over the years, logarithmic ampli ment of terms, some quite misleading attempts to classify log amps into d and application domain and try to be nomenclature. For details, see Analog

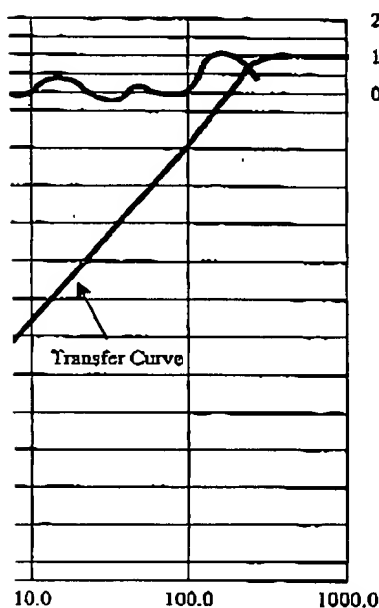
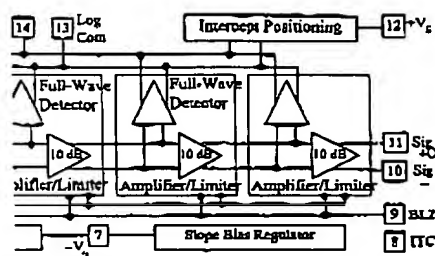
**TABLE 8-1** Key parameters of

Parameter	
Noise	Noise refer may be e density ( voltage (
Dynamic range	Range of sig logarith
Frequency response	Range of fre correctly
Slope	Gradient of l
Intercept point	Value of inp
Log linearity	Deviation of axes) fro

**TABLE 8-2** Types of log amps an sion of Analog Devices, Inc.)

Type	
Translinear log amps	Based on l bipolar perform
Baseband log amps	Respond to input, " used, s amp" a input
Demodulating log amps	AC input : envloj detecti

## d Circuit Block Design



oltage - mV  
er sign)

a) block diagram, (b) transfer function and  
analog Devices, Inc.)

Excellent log linearity over an input range of  
DC to RF applications, the AD-640 is DC  
coupled and used in low-frequency and very low-  
frequency measurements, sonar, and other instruments  
even DC. Unlike many other log amps,  
the AD-640 has absolute accuracy of both slope and  
intercept. Some key features of the AD-

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1. 45 dB dynamic range, two can cascade to 95 dB.
2. Bandwidth DC to 145 MHz (120 MHz when cascaded).
3. Slope of 1 mA/decade, temperature stable.
4. Less than 1 dB log nonlinearity.
5. Balanced circuitry for stability and minimal external components.

For further details on applications, see Analog Devices (1992a, 1992c, 1995).

## 8.4.3 Key Parameters of Log Amps and Classifications

In selecting log amps for a given application, key parameters to be considered are listed in Table 8-1.

Over the years, logarithmic amplifiers have accumulated a confusing assortment of terms, some quite misleading. Here (Table 8-2), Analog Devices, Inc. attempts to classify log amps into three broad groups according to structure and application domain and try to be consistent in matters of terminology and nomenclature. For details, see Analog Devices (1992a, Section 9).

TABLE 8-1 Key parameters of log amps

Parameter	Description
Noise	Noise referred to the input (RTI) of the log amp, which may be expressed as a noise figure, as noise spectral density (voltage, current, or both), or as noise voltage (or noise current or both)
Dynamic range	Range of signal over which the amplifier behaves in a logarithmic manner (expressed in decibels)
Frequency response	Range of frequencies over which the log amp functions correctly
Slope	Gradient of transfer characteristic in V/dB or mA/dB
Intercept point	Value of input signal at which output is 0
Log linearity	Deviation of transfer characteristic (plotted on log/line axes) from a straight line (expressed in decibels)

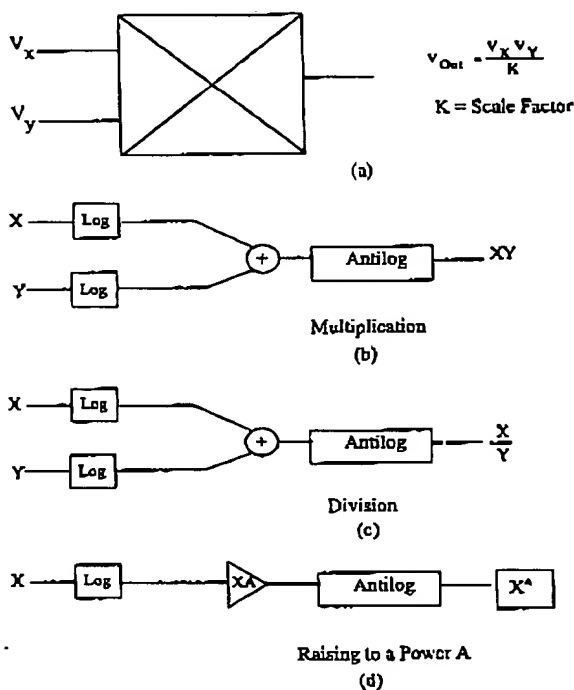
TABLE 8-2 Types of log amps and their behavior. (Reproduced by permission of Analog Devices, Inc.)

Type	Performance
Translinear log amps	Based on logarithmic (or translinear) properties of bipolar transistors; wide dynamic range, poor AC performance
Baseband log amps	Respond to instantaneous value of rapidly changing input, "progressive compression technique" often used, sometimes called <i>video log amps</i> , "true log amp" accepts bipolar inputs sign of output following input
Demodulating log amps	AC input signal is rectified, output is the modulated envelope of the input, often called <i>successive detection log amp</i>

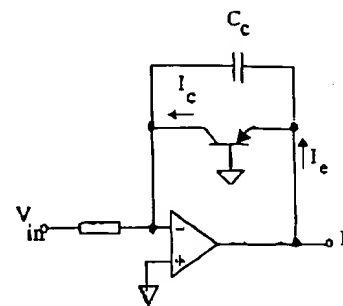
## 354 Modern Component Families and Circuit Block Design

## 8.5 Multipliers and Dividers

A multiplier is a device having two input ports and an output port. The signal at the output is the product of the two input signals. If both input and output signals are voltages, the transfer characteristic is the product of the two voltages divided by a scaling factor,  $K$ , which has the dimension of voltage (see Figure 8-12(a)). From a mathematical point of view, multiplication is a four-quadrant operation; that is to say, both inputs may be either positive or negative, as may be the output. Some of the circuits used to produce electronic multipliers, however, are limited to signals of one polarity. If both signals must be unipolar, we have a single-quadrant multiplier and the output also is unipolar. If one of the signals is unipolar, but the other may have either polarity, the multiplier is a two-quadrant multiplier and the output may have either polarity (and is bipolar). The circuitry used to produce one- and two-quadrant multipliers may be simpler than that required for four quadrant multipliers; and since in many applications full four-quadrant multiplication is not required, it is common to find accurate devices that work only in one or two quadrants.



**FIGURE 8-12** Analog multiplier: (a) basic block diagram, (b) multiplication, (c) division, (d) raising to a power  $A$



**FIGURE 8-13** Log converter compensation

Many techniques can be used for discussed in Sheingold (1976). Most circuits or the use of a Gilbert cell (C Analog Devices is such a monolithic i

Some disadvantages of such circuit of its bandwidth with the signal amplifier arises from the variation of emitter resistance of the base transistor. With reference to Figure 8-13, the emitter current, being approximately constant, is inversely proportional to the compensation capacitor or merely proportional to the transistor current. Therefore, if the dynamic range is 120 dB, its bandwidth is inconvenient. For details, see Analog Devices.

In addition to adopting other improved techniques, a popular technique used in commercial multipliers is the use of a linear relationship between the base-emitter voltage of a transistor and its transconductance (gain).

$$\frac{dI_c}{dV_{BE}}$$

where

$I_c$  = collector current

$V_{BE}$  = base-emitter voltage

$q$  = electron charge

$k$  = Boltzmann's constant

$$q/kT = 1/(25.69 \text{ mV})$$

This relationship may be exploited by using a pair of silicon transistors (Analog Devices).

## Circuit Block Design

Two input ports and an output port. The two input signals. If both input and output characteristic is the product of the two which has the dimension of voltage (see point of view, multiplication is a four-quadrant multiplier may be either positive or negative, used to produce electronic multipliers, polarity. If both signals must be unipolar, the output also is unipolar. If one of the signals have either polarity, the multiplier is a bipolar multiplier (and is bipolar). Four-quadrant multipliers may be simpler multipliers; and since in many applications required, it is common to find accurate multipliers.

$$V_{out} = \frac{V_x V_y}{K}$$

K = Scale Factor

(a)

Antilog — XY

Multiplication

(b)

Antilog —  $\frac{X}{Y}$ 

Division

(c)

Antilog —  $X^A$ 

Raising to a Power A

(d)

= block diagram, (b) multiplication, (c) division, (d) raising to a power A

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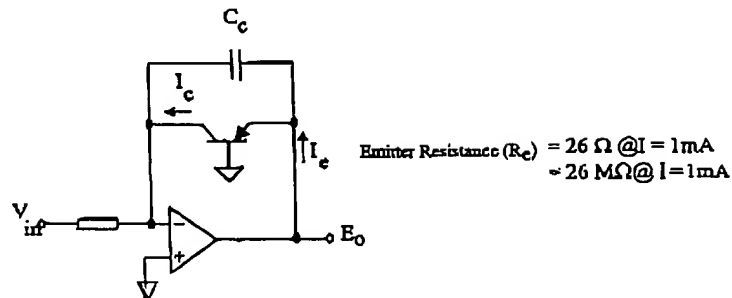


FIGURE 8-13 Log converter compensation problem

Many techniques can be used for analog multipliers, and some of these are discussed in Shengold (1976). Most common forms are the use of log/antilog circuits or the use of a Gilbert cell (Gilbert, 1968a, 1968b). The AD-538 from Analog Devices is such a monolithic integrated circuit (Figure 8-8).

Some disadvantages of such circuits are its unipolar inputs and the variation of its bandwidth with the signal amplitude. The problem of bandwidth variation arises from the variation of emitter resistance,  $R_E$ , with current in the grounded-base transistor. With reference to Figure 8-13,  $R_E$  is inversely proportional to the emitter current, being approximately  $26 \Omega$  at  $1 \text{ mA}$ . The bandwidth of the circuit is inversely proportional to the product of  $R_E C_C$  ( $C_C$  may be an external compensation capacitor or merely stray capacitance) and thus is proportional to the transistor current. Therefore, if the logarithmic converter works over a 120 dB dynamic range, its bandwidth will vary by 1 million:1, which can be inconvenient. For details, see Analog Devices (1987).

In addition to adopting other improved logarithmic conversion techniques, a popular technique used in commercial analog multiplier ICs is the Gilbert cell. There is a linear relationship between the collector current of a silicon junction transistor and its transconductance (gain) that is given by the following equation:

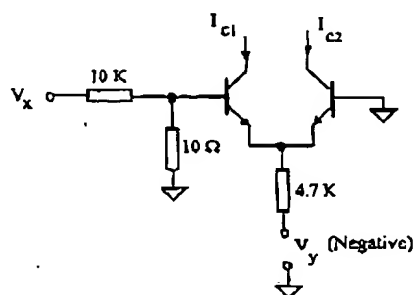
$$\frac{dI_c}{dV_{BE}} = \frac{q}{kT} I_c \quad (8.16)$$

where

 $I_c$  = collector current; $V_{BE}$  = base-emitter voltage; $q$  = electron charge ( $1.60219 \times 10^{-19}$ ); $k$  = Boltzmann's constant ( $1.38062 \times 10^{-23}$ ); $q/kT = 1/(25.69 \text{ mV})$  at  $25^\circ\text{C}$ .

This relationship may be exploited to construct a multiplier with a long-tailed pair of silicon transistors (Analog Devices, 1987), as shown in Figure 8-14.

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**FIGURE 8-14** Basic transconductance multiplier circuit

At 25°C, this circuit provides an output of  $q/kT[(V_y + V_{BE})/(4.7 \times 10^3)] (10/10,010)V_x$  for the case of  $I_{c1} - I_{c2} = \Delta I_c$ .

However, this is a rather poor multiplier because

1. The  $y$  input is offset by the  $V_{BE}$ , which changes nonlinearly with  $V_y$ .
2. The  $x$  input is nonlinear as a result of the exponential relationship between  $I_c$  and  $V_{BE}$ .
3. The scale factor varies with temperature.

Gilbert realized that this circuit could be linearized and made temperature stable by working with currents rather than voltages and by exploiting the logarithmic properties of transistors, as per the case shown in Figure 8-15(a).

The  $x$  input to the Gilbert cell takes the form of a differential current, and the  $y$  input is a unipolar current. The differential  $x$  currents flow in two diode-connected transistors, and the logarithmic voltages compensate for the exponential  $V_{BE}/I_c$  relationship. Furthermore, the  $q/kT$  scale factors cancel each other. This gives the Gilbert cell the linear transfer function for  $I_c = (I_{c1} - I_{c2})$ :

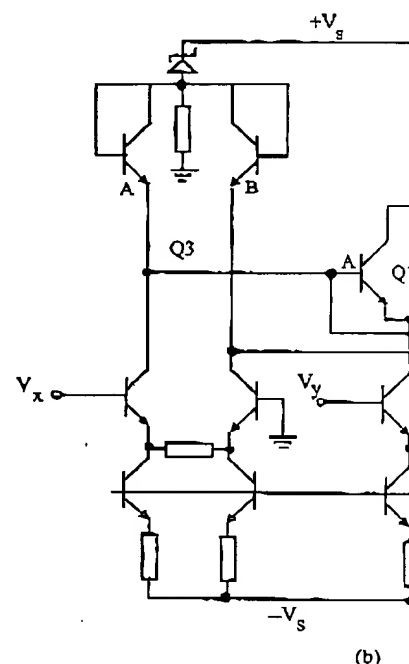
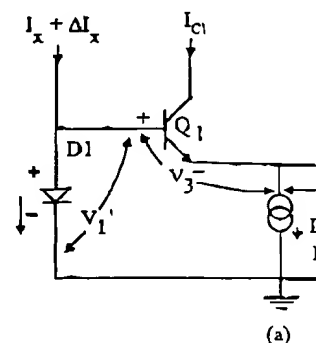
$$\Delta I_c = \frac{\Delta I_x I_y}{I_x} \quad (8.17)$$

As it stands, the basic Gilbert cell shown in Figure 8-15(a) has three inconvenient features:

1. Its  $x$  input is a differential current.
2. Its output is a differential current.
3. Its  $y$  input is a unipolar current.

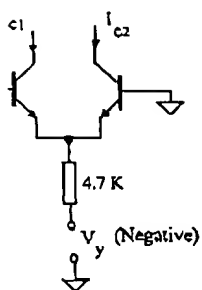
This makes the cell a two-quadrant multiplier.

By cross-coupling two such cells and using two voltage-to-current converters (as shown in Figure 8-15(b)), we can convert the basic architecture to a four-quadrant device with voltage inputs. A practical example of this type of a multiplier is the AD-534 from Analog Devices. In Figure 8-15(b), Q1A and Q1B

**FIGURE 8-15** (a) Two-quadrant and (1) cell. (Reproduced by permission of Analog

and Q2A and Q2B form the two core 1 while Q3A and Q3B are the linearizing shows an operational amplifier acting voltage converter; but for higher spec tors of Q1 and Q2 form a differential

## Circuit Block Design



multiplier circuit

put of  $q/kT[(V_y + V_{BE})/(4.7 \times 10^3)]$   
 $= \Delta I_c$ .

plier because

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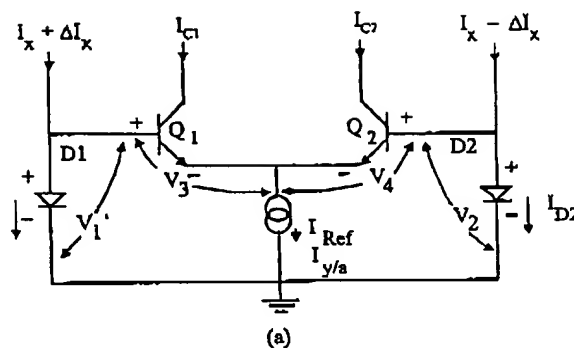
$$\frac{\Delta I_x I_y}{I_x} \quad (8.17)$$

own in Figure 8-15(a) has three incon-

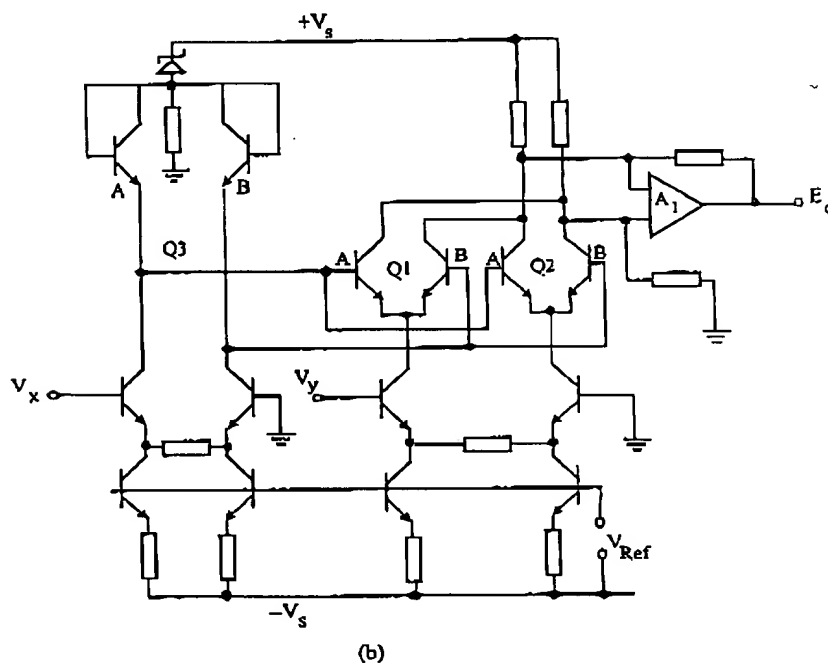
plier.

using two voltage-to-current converters  
 invert the basic architecture to a four-  
 practical example of this type of a  
 ices. In Figure 8-15(b), Q1A and Q1B

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(a)



(b)

**FIGURE 8-15** (a) Two-quadrant and (b) four-quadrant multipliers based on Gilbert cell. (Reproduced by permission of Analog Devices, Inc.)

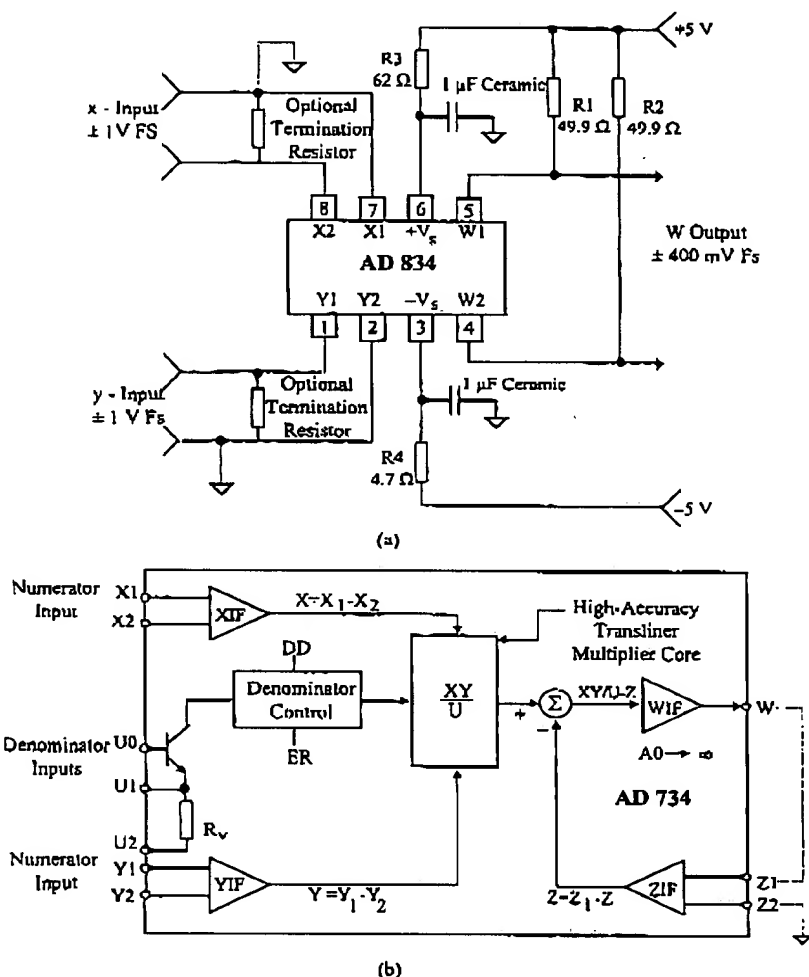
and Q2A and Q2B form the two core long-tailed pairs of the two Gilbert cells, while Q3A and Q3B are the linearizing transistors for both cells. Figure 8-15(b) shows an operational amplifier acting as a differential current to single-ended voltage converter, but for higher speed applications, the cross-coupled collectors of Q1 and Q2 form a differential open collector current output (as in the

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AD-834 multiplier with a 500 MHz range). Motorola's MC 1494 and 1495 are other examples of four-quadrant multipliers.

A basic wideband multiplier using the AD-834 (for 500 MHz bandwidth) is shown in Figure 8-16(a). Figure 8-16(b) indicates the block diagram of a 10 MHz multiplier with direct-divide capability.

For details on multipliers, see Analog Devices (1995, Section 3).



**FIGURE 8-16** Practical multipliers: (a) A wideband application using the AD-834. (b) a 10 MHz multiplier with direct-divide capability using the AD-734. (Reproduced by permission of Analog Devices, Inc.)

## 8.6 RMS-to-DC Converters

The root mean square (RMS) is a measure of an AC signal. Defined practically, the RMS value of an AC signal is the amount of DC required to produce the same average power in the same load. Defined mathematically, the RMS value is the square root of the average value obtained by squaring the signal. The averaging time must be long enough to cover the lowest frequencies of operation desired. RMS-to-DC converters can be found in many multimeters and are discussed in Kularaj in RMS-to-DC converters: explicit and

### 8.6.1 Explicit Method

The explicit method is shown in Figure 8-17. The average value of an AC signal is squared by a multiplier. The square root is taken using an op-amp. This circuit has limited dynamic range because the squarer must try to deal with a signal that restricts the method to inputs with a maximum range of 10:1 (20 dB). However, excellent accuracy can be achieved with high accuracy if a multiplier is used as a building block (see Figure 8-17(b)).

### 8.6.2 Implicit Method

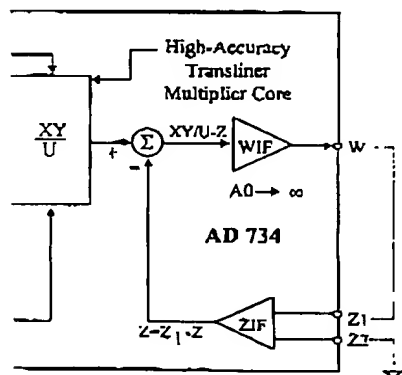
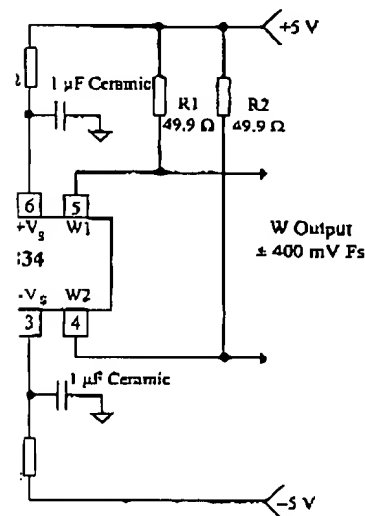
Figure 8-18 shows the circuit for using the implicit method. Here, the output of a multiplier such as the AD-734 is used to vary linearly (instead of as the square) the dynamic range of the multiplier. The disadvantage of the implicit method is the lower bandwidth than the explicit computation.

### 8.6.3 Monolithic RMS/DC Converter

While it is possible to construct such a circuit, it is far simpler to design a dedicated RMS-to-DC converter driven and only one quadrant if the input is a positive signal. Figure 8-19(a) shows a block diagram of a dedicated RMS-to-DC converter such as the AD-536. It is a subdivider circuit (active rectifier), squarer/divider. The input voltage,  $V_{in}$ , which can be a current,  $I_{in}$ , by an absolute value circuit, is squared by a squarer/divider, which has the transfer function

## d Circuit Block Design

(gc). Motorola's MC 1494 and 1495 are  
iers.  
the AD-834 (for 500 MHz bandwidth) is  
indicates the block diagram of a 10 MHz  
log Devices (1995, Section 3).



A wideband application using the AD-834,  
pability using the AD-734. (Reproduced by

## 8.6 RMS-to-DC Converters

The root mean square (RMS) is a fundamental measurement of the magnitude of an AC signal. Defined practically, the RMS value assigned to the AC signal is the amount of DC required to produce an equivalent amount of heat in the same load. Defined mathematically, the RMS value of a voltage is the value obtained by squaring the signal, taking the average, and then taking the square root. The averaging time must be sufficiently long to allow filtering at the lowest frequencies of operation desired. A complete discussion of RMS-to-DC converters can be found in Kitchen and Counts (1986) and application of these in multimeters are discussed in Kularatna (1996). Two basic techniques are used in RMS-to-DC converters: explicit and implicit.

## 8.6.1 Explicit Method

The explicit method is shown in Figure 8-17(a). The input signal is first squared by a multiplier. The average value is taken by using an appropriate filter, and the square root is taken using an op amp with a second squarer in the feedback loop. This circuit has limited dynamic range because the stages following the squarer must try to deal with a signal that varies enormously in amplitude. This restricts the method to inputs with a maximum dynamic range of approximately 10:1 (20 dB). However, excellent bandwidth (greater than 100 MHz) can be achieved with high accuracy if a multiplier such as the AD-834 is used as a building block (see Figure 8-17(b)).

## 8.6.2 Implicit Method

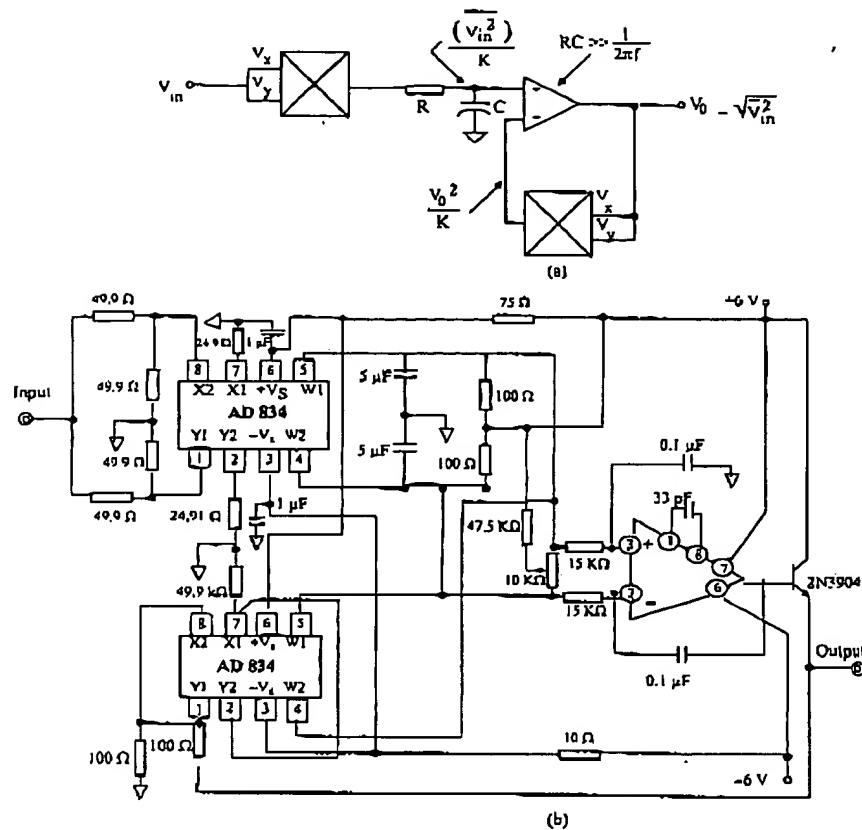
Figure 8-18 shows the circuit for computing the RMS value of a signal using the implicit method. Here, the output is fed back to the direct-divide input of a multiplier such as the AD-734. In this circuit, the output of the multiplier varies linearly (instead of as the square) with the RMS value of the input. This considerably increases the dynamic range of the implicit circuit as compared to the explicit circuit. The disadvantage of this approach is that it generally has less bandwidth than the explicit computation.

## 8.6.3 Monolithic RMS/DC Converters

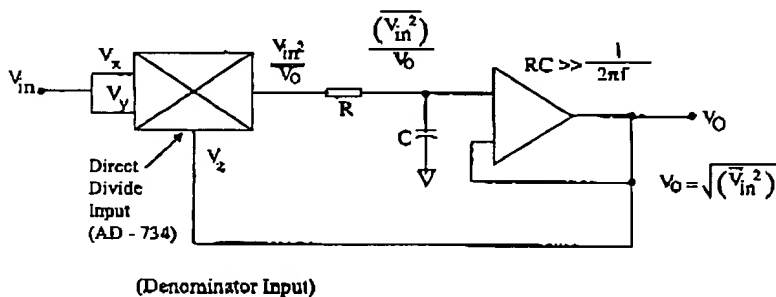
While it is possible to construct such an RMS circuit from an AD-734, it is far simpler to design a dedicated RMS circuit. The  $V_{in}^2/V_z$  circuit may be current driven and only one quadrant if the input first passes through an absolute value circuit. Figure 8-19(a) shows a block diagram of a typical monolithic RMS/DC converter such as the AD-536. It is subdivided into four major sections: absolute value circuit (active rectifier), squarer/divider, current mirror, and buffer amplifier. The input voltage,  $V_{in}$ , which can be AC or DC, is converted to a unipolar current,  $I_{in}$ , by an absolute value circuit.  $I_{in}$  drives one input of the one-quadrant squarer/divider, which has the transfer function  $I_{in}^2/I_f$ . The output current,  $I_{in}^2/I_f$ ,



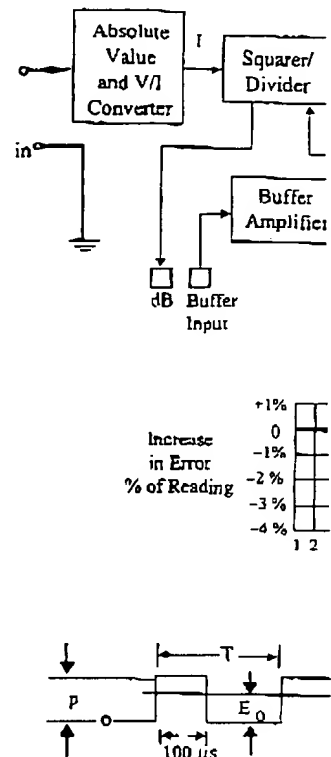
## 360 Modern Component Families and Circuit Block Design



**FIGURE 8-17** The explicit method of RMS-to-DC conversion: (a) basic technique, (b) wideband RMS measurement using the AD-834. (Reproduced by permission of Analog Devices, Inc.)



**FIGURE 8-18** Implicit RMS computation



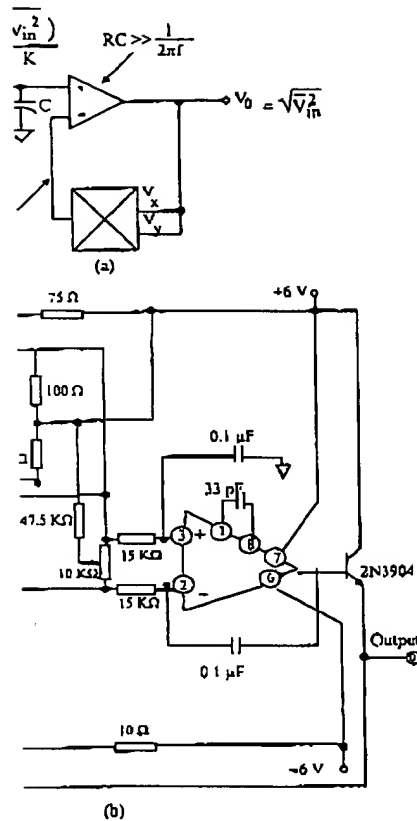
**FIGURE 8-19** The AD-536 RMS/DC crest factor, (c) input waveform used for Devices, Inc.)

of the squarer/divider drives the current by  $R_1$  and an externally connected capacitor much greater than the longest period of averaged. The current mirror returns a value of  $I_m^2/I_f$  back to the squarer/divider. Therefore,

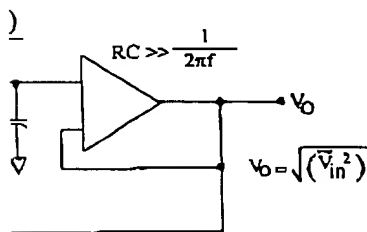
$$I_f = \left( \frac{I_m^2}{I_f} \right)$$

The current mirror also produces the output. The circuit provides a decibel output of approximately 3300 ppm/°C and mu:

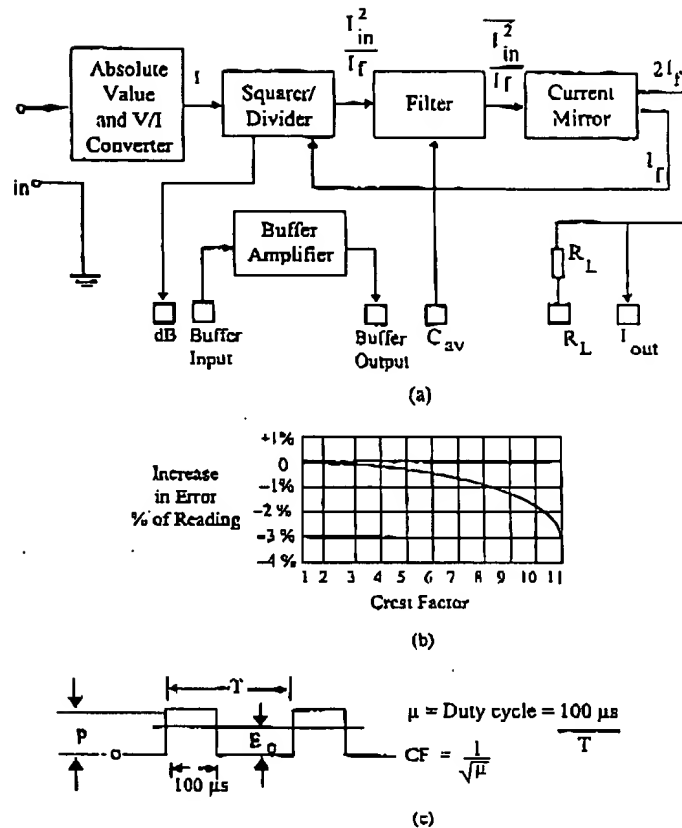
## Circuit Block Design



IS-to-DC conversion: (a) basic technique, 834. (Reproduced by permission of Analog



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**FIGURE 8-19** The AD-536 RMS/DC converter: (a) block diagram, (b) error against crest factor, (c) input waveform used for (b). (Reproduced by permission of Analog Devices, Inc.)

of the squarer/divider drives the current mirror through a low-pass filter formed by  $R_f$  and an externally connected capacitor,  $C_{AV}$ . If the  $R_f C_{AV}$  time constant is much greater than the longest period of the input signal, then  $I_{in}^2/I_f$  is effectively averaged. The current mirror returns a current,  $I_f$ , that equals the average value of  $I_{in}^2/I_f$  back to the squarer/divider to complete the implicit RMS computation. Therefore,

$$I_f = \left( \frac{I_{in}^2}{I_f} \right) = I_{in}(RMS) \quad (8.18)$$

The current mirror also produces the output current,  $I_{out}$ , which equals  $2I_f$ . The circuit provides a decibel output also, which has a temperature coefficient of approximately 3300 ppm/ $^{\circ}$ C and must be temperature compensated.





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Trigonometric functions more normally are calculated by the AD-639. No external components (other than supply decoupling capacitors) are required to compute sines, cosines, tangents and cotangents, and secants and cosecants with the AD-639. Little more than an extra reference voltage (which may be generated from the internal reference with an operational amplifier and a couple of resistors) is required for versines and coversines. For details of the less common functions, consult the AD-639 data sheet (Analog Devices, 1999) and various application notes—the sine, cosine, and tangent will be described here. Some interesting applications of the AD-639 are discussed in Analog Devices (1987).

## 8.8 Benistor, a Newly Introduced Device

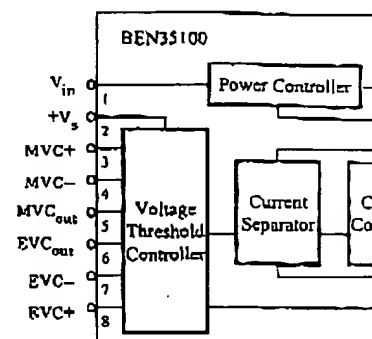
An interesting novel component surfaced recently (Bindra, 1998) from the Bensys Corporation, the Benistor™. (The name Benistor is a combination of the company's name and transistor.) The Benistor, which performs similar to multielectrode vacuum tubes, can independently control the voltage and current output from the device.

Introduced in 1998, the device block diagram, shown in Figure 8-21(a), comprises four blocks: the power controller (PC), the current separator (CS), the current controller (CC), and the voltage threshold controller (VTC). In the first commercial device, BEN 35100, the PC is a simple PNP transistor that acts as a switch or a variable resistor between the power source and the load. The CS block incorporates three NPN transistors to enable the voltage controller and current controller to work simultaneously or separately.

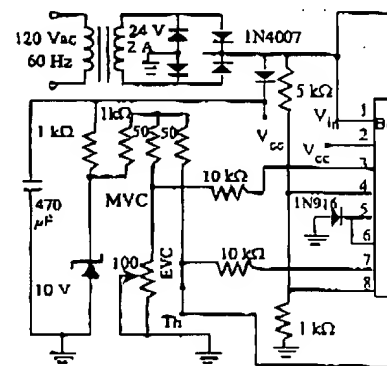
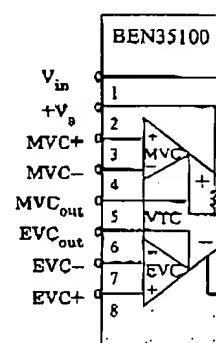
Comprising two open-collector op.amps and two resistors, the current controller acts as a voltage/current converter for the power controller. There are two control inputs to this block: the noninverting input CC and the inverting input CC. The amount of voltage input at the noninverting current control is directly proportional to the current output to the load, and the amount of voltage at the inverting electrode is inversely proportional to the output current. Functioning as a window comparator, the VTC controls the buffer's base current, in either a switching or self-switching mode. The two controls of the VTC are effective voltage control (EVC) and maximum voltage control (MVC), which determine the threshold voltages of the output. While the voltage at the EVC establishes the threshold for switching from off to on, the voltage at MVC pin determines the on/off states. In effect, the voltage settings on these two pins pre-establish the output voltage window.

In summary, the Benistor is a multielectrode device consisting of impedance command pins for precise control of output current and voltage. Consequently, eight electrodes completely define the Benistor. These are shown in Figure 8-21(b).

The SS electrode (not used in the BEN 35100 version) sets the initial state of the Benistor's self-switching mode of operation as either on or off at the beginning of an input power pulse wave. Having only two states, it is either grounded (on) or floating (off). Likewise, the CE provides the reference voltage



(a)



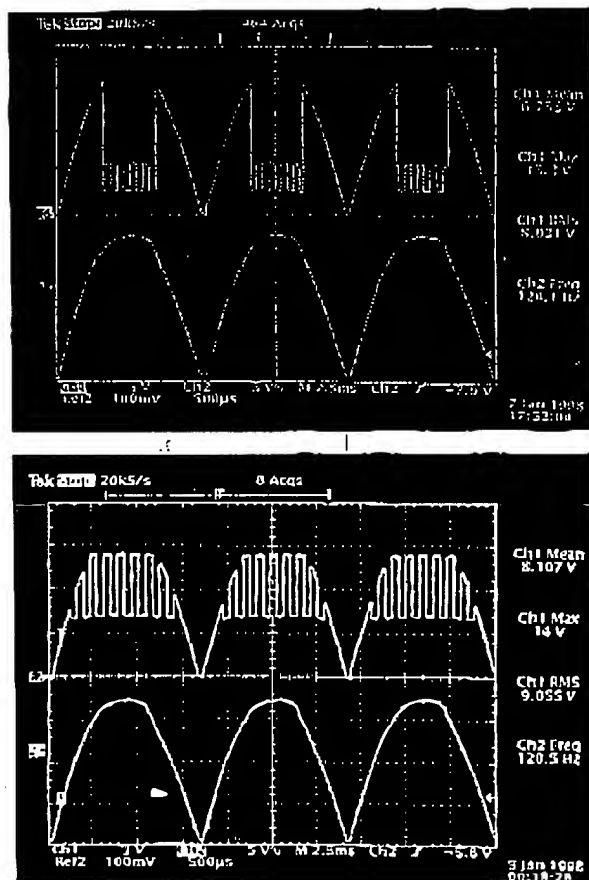
**FIGURE 8-21** The Benistor: (a) block diagram, (b) pinout, (c) a soldering iron application circuit, (d) a soldering iron application by permission of the Bensys Corporation.



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for the device, while the CC determines the window of output current, and the VTC pre-establishes the window of output voltage. Based on these settings, the power controller will deliver to the load only that part of the input power signal, with respect to the amount of current and voltage, within the two pre-established ranges. In effect, together, the voltage and current-control electrodes can provide the system designer virtually any output possibility.

Because the device can accept AC, DC, and pulse input and provide output in any of these modes or any combination (based on conditions at the control electrodes), the Benistor inspires a new way of thinking in power control and power conversion. Combining the capability of all three previous values, it provides designers a unique method of controlling power parameters. Figure 8-22 indicates



**FIGURE 8-22.** Waveform control example. (Reproduced by permission of Bensys Corporation.)

complex waveforms that can be obtained. For further details, see Bindra (1998), ●●● and U.S. Patent No. 5,598,093.

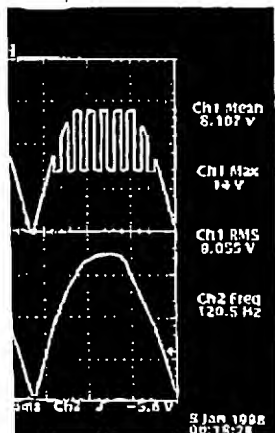
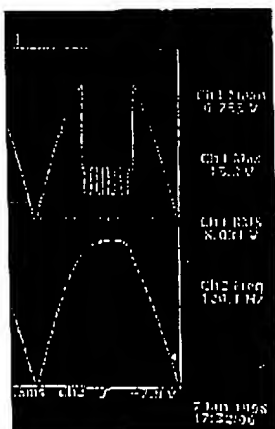
### References

- Analog Devices. Linear Design Seminar. Analog Devices.
- Analog Devices. High Speed Design Seminar. / Analog Devices.
- Analog Devices. *Amplifier Applications Guide*. Analog Devices.
- Analog Devices. *High Speed Design Techniques*. Analog Devices.
- Analog Devices. "AD640: DC Coupled Demodulator." *Linear Reference Manual*, rev. A. Analog Devices 3-46.
- Analog Devices. Linear Design Seminar. Analog Devices.
- Analog Devices. "AD639—Universal Trigonometric Function Generator." Analog Devices, Inc. (Norwood, MA, USA), Design.
- Bensys Corporation. "Preliminary Data Sheet, I USA September 11, 1998.
- Bensys Corporation. "Incandescent Lamp Flasher." Bensys Corporation, CA, USA ●●●.
- Bensys Corporation. "DC to DC Converters." Ap. USA ●●●.
- Bensys Corporation. "Lithium Ion Battery Charger." Bensys Corporation, CA, USA ●●●.
- Bensys Corporation. *User Manual—EB 16 Evaluation Board*. Bensys Corporation, CA, USA ●●●.
- US Patent Number 5,598,093, January 28, 1997: Controlling Energy Delivered to a Load and Method Thereof.
- Bindra, Ashok. "Unique Valve Independently Controlled." *IEEE Transactions on Industrial Electronics*, 1998, pp. 35–40.
- Gilbert, Barrie. *ISSCC Digest of Technical Papers*. IEEE Press, 1998.
- Gilbert, Barrie. *Journal of Solid State Circuits* SC-13, No. 2, February 1978, pp. 169–173.
- Hughes, Richard Smith. *Logarithmic Amplifiers*. IEE Press, 1986.
- Kitchen, Charles, and Lew Counts. *RMS to DC Conversion*. Analog Devices, Inc., 1986.
- Kularatna, N. *Modern Electronic Test and Measurement*. Prentice Hall, 1998.
- Sheingold, Daniel H. *Nonlinear Circuits Handbook*. Analog Devices, Inc., 1986.

## Circuit Block Design

the window of output current, and the it voltage. Based on these settings, the nly that part of the input power signal, voltage, within the two pre-established current-control electrodes can provide possibility.

DC, and pulse input and provide output based on conditions at the control elec- if thinking in power control and power all three previous values, it provides ower parameters. Figure 8-22 indicates



e. (Reproduced by permission of Bensys

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complex waveforms that can be obtained from the same input (bottom traces). For further details, see Bindra (1998), and Bensys Corporation (•••, •••, •••, •••) and U.S. Patent No. 5,598,093.

## References

- Analog Devices. Linear Design Seminar. Analog Devices, Inc., 1987.  
 Analog Devices. High Speed Design Seminar. Analog Devices, Inc., 1990.  
 Analog Devices. *Amplifier Applications Guide*. Analog Devices, Inc. (Norwood, MA, USA) 1992a.  
 Analog Devices. *High Speed Design Techniques*. Analog Devices, Inc. (Norwood, MA, USA) 1992b.  
 Analog Devices. "AD640: DC Coupled Demodulating 120 MHz Logarithmic Amplifier." In *Special Linear Reference Manual*, rev. A. Analog Devices, Inc. (Norwood, MA, USA) 1992c, pp. 3-31 to 3-46.  
 Analog Devices. Linear Design Seminar. Analog Devices, Inc. (Norwood, MA, USA) 1995.  
 Analog Devices. "AD639—Universal Trigonometric Function Converter—Data Sheet." Analog Devices, Inc. (Norwood, MA, USA), Designer's Reference Manual (CD ROM), 1999.  
 Bensys Corporation. "Preliminary Data Sheet, BEN 35100." Bensys Corporation, Sunnyvale, CA, USA September 11, 1998.  
 Bensys Corporation. "Incandescent Lamp Flasher." Application note. Bensys Corporation, Sunnyvale, CA, USA •••.  
 Bensys Corporation. "DC to DC Converters." Application note. Bensys Corporation, Sunnyvale, CA, USA •••.  
 Bensys Corporation. "Lithium Ion Battery Charger." Application note. Bensys Corporation, Sunnyvale, CA, USA •••.  
 Bensys Corporation. *User Manual—EB 16 Evaluation Board*. Bensys Corporation, Sunnyvale, CA, USA •••.  
 US Patent Number 5,598,093, January 28, 1997: "Low Dissipation Controllable Electron Valve for Controlling Energy Delivered to a Load and Method Therefor."  
 Bindra, Ashok. "Unique Valve Independently Controls Power Parameters." *Electronic Design* (July 6, 1998), pp. 35-40.  
 Gilbert, Barrie. *ISSCC Digest of Technical Papers* (February 16, 1968), pp. 114-115.  
 Gilbert, Barrie. *Journal of Solid State Circuits* SC-3 (December 1968), pp. 353-372.  
 Hughes, Richard Smith. *Logarithmic Amplifiers*. Dedham, MA: Artech House, 1986.  
 Kitchen, Charles, and Lew Counts. *RMS to DC Conversion Application Guide*, 2nd ed. Analog Devices, Inc., 1986.  
 Kularatna, N. *Modern Electronic Test and Measuring Instruments*. London: IEEE, 1996.  
 Sheingold, Daniel H. *Nonlinear Circuits Handbook*. Analog Devices, Inc., 1976.



## CHAPTER 9

# Rechargeable Batteries and Their Management

## 9.1 Introduction

The insatiable demand for smaller, lightweight portable electronic equipment has dramatically increased the need for research on rechargeable (or secondary) battery chemistries. In addition to achieving improved performance on lead acid and nickel cadmium (NiCd) batteries, during the last decade, many new chemistries such as nickel metal hydride (NiMH), lithium ion (Li-ion), rechargeable alkaline, silver-zinc, zinc-air, lithium polymer, and the like have been introduced.

Higher energy density, superior cycle life, environmental friendliness, and safe operation are among the general design targets of battery manufacturers. To complement these developments many semiconductor manufacturers have introduced new integrated circuit families to achieve the best charge/discharge performance and longest possible lifetime from battery packs.

This chapter describes the characteristics of battery families such as sealed lead acid, NiCd, NiMH, Li-ion, rechargeable alkaline, and zinc-air together with modern techniques used in battery management ICs, without elaborating on the battery chemistries. Concepts and applications related to systems management bus and smart battery system also are introduced.

## 9.2 Battery Terminology

### 9.2.1 Capacity

Battery or cell capacity is measured as an integral of current ( $i$ ) over a defined period of time ( $t$ ):

$$\text{Capacity} = \int_0^t i \, dt$$

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This equation applies to either the charge or discharge; that is, the capacity added or capacity removed from a battery or cell. The capacity of a battery or cell is measured in milliampere-hours (mAh) or ampere-hours (Ah).

Although the basic definition is simple, many different forms of capacity are used in the battery industry. The distinctions among them reflect differences in the conditions under which the capacity is measured.

**Standard capacity** measures the total capacity that a relatively new but stabilized production cell or battery can store and discharge under a defined standard set of application conditions. It assumes that the cell or battery is fully formed, charged at the standard temperature at the specification rate, and discharged at the same standard temperature at a specified standard discharge rate to a standard end-of-discharge voltage (EODV). The standard EODV itself is subject to variation depending on discharge rate as discussed.

When any of the application conditions differ from standard, the capacity of the cell or battery changes. The term **actual capacity** includes all nonstandard conditions that alter the amount of capacity the fully charged new cell or battery is capable of delivering when fully discharged to a standard EODV. Examples of such situations might include subjecting the cell or battery to a cold discharge or a high-rate discharge.

That portion of actual capacity which can be delivered by the fully charged new cell or battery to some nonstandard EODV is called **available capacity**. Therefore, if the standard EODV is 1.6 volts per cell, the available capacity to an EODV of 1.8 volts per cell would be less than the actual capacity.

**Rated capacity** is the minimum expected capacity when a new but fully formed cell is measured under standard conditions. This is the basis for C rate and depends on the standard conditions used, which may vary depending on the manufacturers and the battery types.

If a battery is stored for a period of time following a full charge, some of its charge will dissipate. The capacity that remains and can be discharged is called the **retained capacity**.

#### 9.2.2 C Rate

The C rate is the rate in amperes or milliamperes numerically equal to the capacity rating of the cell given in ampere-hours or milliamperc-hours. For example, a cell with a 1.2 Ah capacity has a C rate of 1.2 amps. The C concept simplifies the discussion of charging for a broad range of cell sizes, since the cells' responses to charging are similar if the C rate is the same. Normally, a 4 Ah cell will respond to a 0.4 amp (0.1 C) charge rate in the same manner that a 1.4 Ah cell will respond to a 0.14 amp (also 0.1 C) charge rate.

The rate at which current is drawn from a battery affects the amount of energy that can be obtained. At low discharge rates the actual capacity of a battery is greater than at high discharge rates. This relationship is shown in Figure 9-1.

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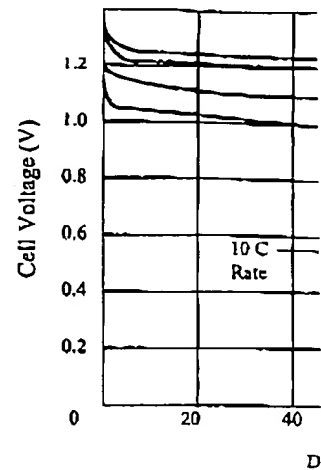


FIGURE 9-1 Capacity vs. discharge rate

#### 9.2.3 Energy Density

The energy density of a cell is its energy per unit mass or volume. This is called the **gravimetric energy density** when volume is used and **specific energy** sometimes are used respectively; Bennett and Brown, 1997.

#### 9.2.4 Cycle Life

Cycle life is a measure of a battery's ability to withstand repeated discharging and recharging using the rated capacity and still provide the minimum required capacity. Cyclic discharge testing can be done to simulate conditions in the field. However, that cycle life has an inverse logarithmic relationship to the energy density.

#### 9.2.5 Cyclic Energy Density

For comparison, a better measure of battery performance is a composite characteristic that combines energy density and cycle life. This composite characteristic is called **cyclic energy density**, the product of energy density and cycle life. It is measured in the dimensional units watt-hour-cycles/liter (volumetric).

## Circuit Block Design

arge or discharge; that is, the capacity of a cell. The capacity of a battery or cell is measured in ampere-hours (Ah).

le, many different forms of capacity measurements among them reflect differences in how capacity is measured.

l capacity that a relatively new but standard method to store and discharge under a defined standard discharge rate assumes that the cell or battery is at a specified standard discharge rate at the specification rate, and is at a specified standard discharge rate (EODV). The standard EODV itself is defined as discussed.

s differ from standard, the capacity of a cell or battery includes all nonstandard capacity that the fully charged new cell or battery is required to deliver at a standard EODV. Examples of the cell or battery to a cold discharge rate as discussed.

can be delivered by the fully charged EODV is called **available capacity**. Its per cell, the available capacity is less than the actual capacity. Actual capacity when a new but fully charged cell is discharged at a standard rate. This is the basis for C rate discharge, which may vary depending on the

ie following a full charge, some of its capacity is lost and can be discharged is called

r milliamperes numerically equal to ampere-hours or milliamperes-hours. For a C rate of 1.2 amps. The C concept is used for a broad range of cell sizes, since the C rate is the same. Normally, a cell is charged at the same rate that it is discharged (also 0.1 C) charge rate.

rom a battery affects the amount of capacity that is lost at high discharge rates. This relationship is shown in

## Rechargeable Batteries and Their Management 371

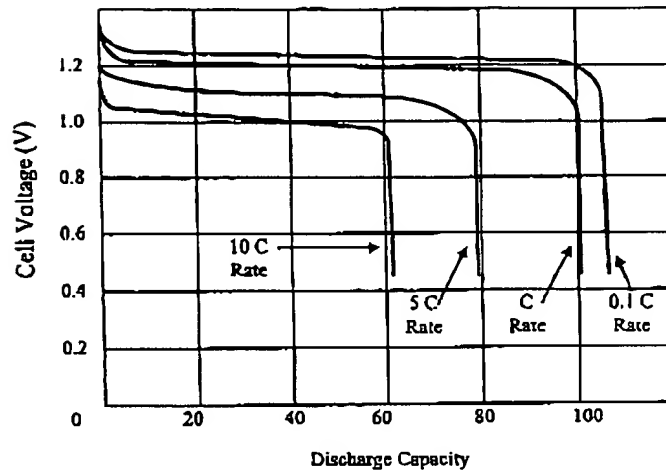


FIGURE 9-1 Capacity vs. discharge rate of a typical cell

### 9.2.3 Energy Density

The energy density of a cell is its energy divided by its weight or volume. This is called the **gravimetric energy density** when weight is used, and the **volumetric energy density** when volume is used. (The terms **energy density** and **specific energy** sometimes are used for volumetric and gravimetric measures, respectively; Bennett and Brown, 1997.)

### 9.2.4 Cycle Life

Cycle life is a measure of a battery's ability to withstand repetitive deep discharging and recharging using the manufacturer's cyclic charging recommendations and still provide the minimum required capacity for the application. Cyclic discharge testing can be done at any of various rates and depths of discharge to simulate conditions in the application. It must be recognized, however, that cycle life has an inverse logarithmic relationship to depth of discharge.

### 9.2.5 Cyclic Energy Density

For comparison, a better measure of rechargeable battery characteristics is a composite characteristic that considers energy density over the service life of the battery. This composite characteristic, **cyclic energy density**, is the product of energy density and cycle life at that energy density and measured in the dimensional units watt-hour-cycles/kilogram (gravimetric) or watt-hour-cycles/liter (volumetric).

### 9.2.6 Self-Discharge Rate

The self-discharge rate is a measure of how long a battery can be stored and still provide the minimum required capacity and be rechargeable to the rated capacity. This commonly is measured by placing batteries on shelf at room (or elevated) temperature and monitoring open circuit voltage over time. Samples are discharged at periodic intervals to determine remaining capacity and recharged to determine rechargeability.

### 9.2.7 Charge Acceptance

Charge acceptance is the willingness of a battery or cell to accept a charge. This is affected by cell temperature, charge rate, and the state of charge.

### 9.2.8 Depth of Discharge

The depth of discharge is the capacity removed from a battery divided by its actual capacity, expressed as a percentage.

### 9.2.9 Voltage Plateau

The voltage plateau is the protracted period of very slowly declining voltage that extends from the initial voltage drop at the start of a discharge to the knee of the discharge curve (Figure 9-2).

### 9.2.10 Midpoint Voltage

The midpoint voltage is the battery voltage when 50% of the actual capacity has been delivered (see Figure 9-2).

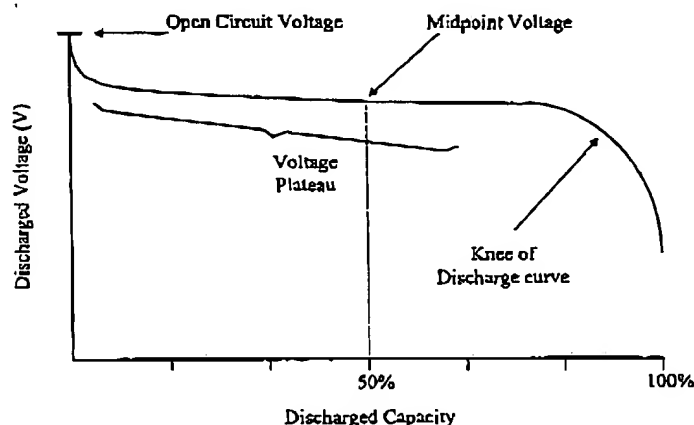


FIGURE 9-2 Nominal discharge performance for sealed lead-acid cells

### 9.2.11 Overcharge

Overcharge is the continued charging. When a cell is not yet fully charged, current is converted to chemical energy when all the available active material energy available in the charging current is used to activate other nonuseful chemical

## 9.3 Battery Technology:

Many types of rechargeable chemical batteries are available. The most common are NiCd, NiMH, and lead acid. They are used in a wide headway into portable systems. The performance of a given system is typically limited by the battery chemistry. A comparison of some basic characteristics of various battery chemistries is depicted in Table 9-1.

NiCd batteries presently power most portable systems. This technology is mature and well understood. Increasing regulatory scrutiny (including RoHS and REACH) and the maturity of NiCd technology have led to life cycle improvements already have been implemented.

NiMH offers incremental improvement in energy density and volume over NiCd. Li-ion is better in terms of energy density and per kilogram of NiCd batteries. At a higher price, NiMH and Li-ion are used in applications that support a higher performance. NiMH and Li-ion chemistry, however, are still relatively new.

TABLE 9-1 Battery chemistry characteristics

Parameter	Units/Conditions	Sealed Lead Acid
Cell voltage	Volts	2.0
Relative cost	NiCd = 1	0.6
Self-discharge	%/month	2-4%
Cycle life	Cycles to reach 80% of rated capacity	500-2000
Overcharge tolerance	—	High
Energy by volume	Watt hour/liter	70-110
Energy by weight	Watt hour/kg	30-45

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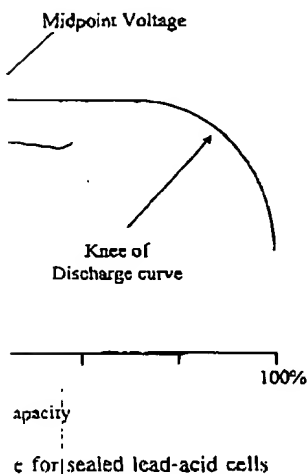
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## 9.2.11 Overcharge

Overcharge is the continued charging of a cell after it has become fully charged. When a cell is not yet fully charged, the electrical energy of the charge current is converted to chemical energy in the cell by the charging reactions. But, when all the available active material has been converted to a charged state, the energy available in the charging current goes to produce gases from the cell or to activate other nonuseful chemical reactions.

## 9.3 Battery Technology: An Overview

Many types of rechargeable chemistry are used in electronic systems. Today, most batteries are NiCd, NiMH, and sealed lead acid, with lithium-ion making headway into portable systems. The choice of a particular battery technology for a given system is typically limited by size, weight, cycle life, and cost. A comparison of some basic characteristics of the five major types of battery chemistry is depicted in Table 9-1.

NiCd batteries presently power most rechargeable consumer appliances. The technology is mature and well understood. However, cadmium is coming under increasing regulatory scrutiny (including mandatory recycling in some jurisdictions) and the maturity of NiCd technology also means most of the capacity and life cycle improvements already have been made.

NiMH offers incremental improvements in energy density both by weight and volume over NiCd. Li-ion is better still, offering over twice the watts per liter and per kilogram of NiCd batteries. As always, this higher performance comes at a higher price. NiMH and Li-ion are increasing in popularity as upgrade options or in applications that support a higher price/performance point. The advantages of NiMH and Li-ion chemistry, however, also come at the cost of greater electrical

TABLE 9-1 Battery chemistry characteristics

Parameter	Units/Conditions	Sealed Lead Acid	NiCd	NiMH	Li-ion	Rechargeable Alkaline
Cell voltage	Volts	2.0	1.2	1.2	3.6	1.5
Relative cost	NiCd = 1	0.6	1	1.6	2	0.5
Self-discharge	%/month	2-4%	15-30%	18-20%	6-10%	0.3%
Cycle life	Cycles to reach 80% of rated capacity	500-2000	500-1000	500-800	1000-1200	<25
Overcharge tolerance	—	High	Medium	Low	Very low	Medium
Energy by volume	Watt hour/liter	70-110	120-150	250-300	280-320	220
Energy by weight	Watt hour/kg	30-45	40-50	70-80	110-130	80

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fragility. Li-ion particularly is more easily and extensively damaged by less than optimal battery management, so much so that fail-safe circuits to disconnect the cells from the load under overcurrent or overtemperature conditions usually are built into the battery pack.

Rechargeable alkaline batteries mimic the form and replace the function of disposable household batteries. While initially more expensive, they cost less over their lifetime than the equivalent in disposable batteries. They are the least expensive form of rechargeable chemistry for low current applications and have the lowest self-discharge rate. However, they have the shortest cycle life in deep discharge applications.

Lead-acid batteries are most familiar in automobiles because they are the most economical chemistry for delivering large currents. Lead-acid batteries also have a long trickle life and therefore serve well for classic "floating" applications. Although flooded lead-acid technology is popular for automobile and similar applications, sealed lead-acid batteries serve the electronic engineering environment. On the downside, lead-acid has the least capacity by volume and weight.

Table 9-1 lists the major advantages and disadvantages of the five chemistries. Chemistry selection involves trade-offs driven by the technical requirements and economics of the application.

## 9.4 Lead-Acid Batteries

### 9.4.1 Flooded Lead-Acid Batteries

The flooded lead-acid battery of today basically uses the design developed by Faure in 1881. It consists of a container with multiple plates immersed in a pool of dilute sulfuric acid. Recombination is minimal, so water is consumed throughout the battery life and the batteries can emit corrosive and explosive gases when experiencing overcharge. So-called maintenance-free forms of flooded batteries provide excess electrolytes to accommodate water loss throughout a normal life cycle. Most industrial applications for flooded batteries are found in motive power, engine starting, and large system power backup. Today, other forms of battery have largely supplanted flooded batteries in small- and medium-capacity applications, but in larger sizes flooded lead-acid batteries continue to dominate. By far, the biggest application for flooded batteries is starting, lighting, and ignition service on automobiles and trucks. Large flooded lead-acid batteries also provide motive power for equipment ranging from forklifts to submarines and provide emergency power backup for many electrical applications, most notably the telecommunication network.

### 9.4.2 Sealed Lead-Acid Batteries

Sealed lead-acid batteries first appeared in commercial use in the early 1970s. Although the governing reactions of the sealed cell are the same as other

forms of lead-acid batteries, the key occurs in the sealed cell as it reaches acid systems, the excess energy from of water in the electrolyte with the because the excess electrolyte prevents plate and possibly recombining. This must be replenished. The sealed-lead uses recombination to reduce or eliminate.

Sealed lead-acid batteries for electric from the type commonly found in the lead-acid batteries: the original gell system. The gelled electrolyte system an electrolyte, causing it to set up in a fine glass fiber separator to absorb the retained system is called an absorbed known as a *starved design*. Starved separator create a limitation to the ties of the separator. In certain cases trayed in a specific position for optimal AGM, are called *valve regulated lead* cells are operating effectively in many batteries. For a detailed account of lead (1992), Hirai (1990), and Moore (199 introduced special versions of sealed energy density; for example, the Po series and the Bolder Technologies Co with comparatively higher energy density Nelson, 1997).

#### 9.4.2.1 Discharge Performance

The general shape of the discharge (if the current is uniform) is shown in starved-electrolyte sealed-lead acid battery until most of its capacity is discharged and the length of the voltage plateau. The major features of sealed-lead cells and leaves the plateau and begins to decline the curve. Starved-electrolyte sealed-lead a wide range of temperatures. They may environments and may produce actual capacity when used in hot environments. Figure capacity and cell temperature. Actual rated capacity as measured at 23°C.

## Circuit Block Design

and extensively damaged by less than at fail-safe circuits to disconnect the temperature conditions usually are

the form and replace the function of ally more expensive, they cost less sposable batteries. They are the least or low current applications and have y have the shortest cycle life in deep

in automobiles because they are the rge currents. Lead-acid batteries also ve well for classic "floating" appli-logy is popular for automobile and ies serve the electronic engineering as the least capacity by volume and

nd disadvantages of the five chemis-driven by the technical requirements

## ies

asically uses the design developed by multiple plates immersed in a pool of al, so water is consumed throughout corrosive and explosive gases when ance-free forms of flooded batteries water loss throughout a normal life oded batteries are found in motive iver backup. Today, other forms of eries in small- and medium-capacity -acid batteries continue to dominate. utteries is starting, lighting, and igni- rge flooded lead-acid batteries also ig from forklifts to submarines and electrical applications, most notably

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## Rechargeable Batteries and Their Management 375

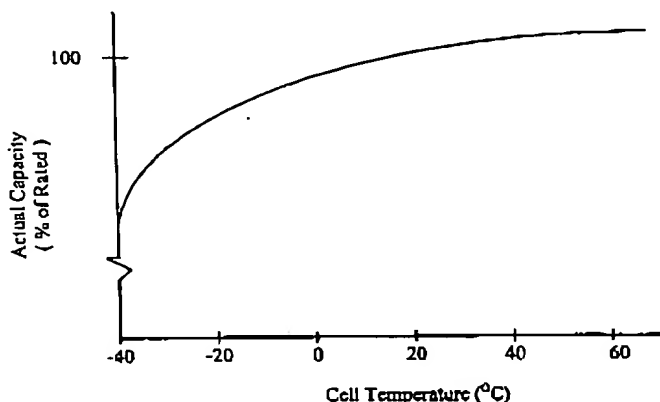
forms of lead-acid batteries, the key difference is the recombination process that occurs in the sealed cell as it reaches full charge. In conventional flooded lead-acid systems, the excess energy from overcharging goes into the electrolysis of water in the electrolyte with the resulting gases being vented. This occurs because the excess electrolyte prevents the gases from diffusing to the opposite plate and possibly recombining. Thus, electrolyte is lost on the overcharge and must be replenished. The sealed-lead cell, like the sealed nickel-cadmium cell, uses recombination to reduce or eliminate this electrolyte loss.

Sealed lead-acid batteries for electronics applications are somewhat different from the type commonly found in the automobile. There are two types of sealed lead-acid batteries: the original gelled electrolyte and retained (or absorbed) system. The gelled electrolyte system is obtained by blending silica gel with an electrolyte, causing it to set up in gelatin form. The retained system employs a fine glass fiber separator to absorb and retain liquid electrolyte. Sometimes the retained system is called an absorbed glass mat (AGM). The AGM also is known as a *starved design*. *Starved* means the absorption limits of the glass separator create a limitation to the AGM design relating to diffusion properties of the separator. In certain cases, the AGM battery must be racked and trayed in a specific position for optimum performance. Both types, gelled and AGM, are called *valve regulated lead acid* (VRLA) systems. Today, sealed-lead cells are operating effectively in many markets previously closed to lead-acid batteries. For a detailed account of lead-acid cells, see Gates Energy Products Inc. (1992), Hirai (1990), and Moore (1993). Meanwhile, some manufacturers have introduced special versions of sealed lead-acid batteries with higher volumetric energy density; for example, the Portable Energy Products, Inc., Thinline™ series and the Bolder Technologies Corporation Thin Metal Film (TMF™), both with comparatively higher energy densities (Moneypenny and Wehmeyer, 1994; Nelson, 1997).

### 9.4.2.1 Discharge Performance of Sealed-Lead Acid Cells

The general shape of the discharge curve, voltage as a function of capacity (if the current is uniform) is shown in Figure 9-2. The discharge voltage of the starved-electrolyte sealed-lead acid battery typically remains relatively constant until most of its capacity is discharged. It then drops off sharply. The flatness and the length of the voltage plateau relative to the length of the discharge are major features of sealed-lead cells and batteries. The point at which the voltage leaves the plateau and begins to decline rapidly often is identified as the knee of the curve. Starved-electrolyte sealed-lead acid batteries may be discharged over a wide range of temperatures. They maintain adequate performance in cold environments and may produce actual capacities higher than their standard capacity when used in hot environments. Figure 9-3 illustrates the relationships between capacity and cell temperature. Actual capacity is expressed as a percentage of rated capacity as measured at 23°C.

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**FIGURE 9-3** Typical discharge capacity as a function of cell temperature

#### 9.4.2.2 Capacity During Battery Life

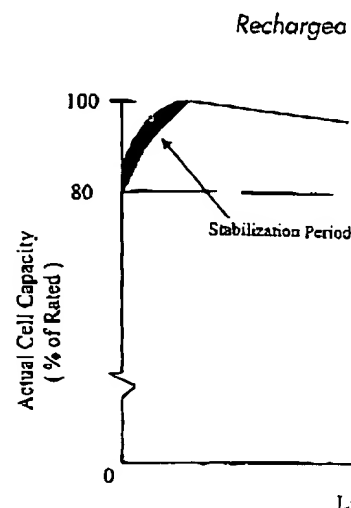
The initial actual capacity of sealed-lead acid batteries is almost always lower than the battery's rated or standard capacity. However, during the battery's early life, the actual capacity increases until it reaches a stabilized value, which usually is above the rated capacity. The number of charge/discharge cycles or length of time on float charge required to develop a battery's capacity depends on the specific regime employed. Alternatively, a battery that is on charge at 0.1 C usually is stabilized after receiving a 300% (of rated capacity) overcharge. The process may be accelerated by charging and discharging at low rates.

Under normal operating conditions, the battery's capacity will remain at or near its stabilized value for most of its useful life. Batteries then will begin to suffer some capacity degradation due to their age and the duty to which they have been subjected. This permanent loss usually increases slowly with age until the capacity drops below 80% of its rated capacity, which often is defined as the end of useful battery life. Figure 9-4 shows the capacity variation with cycle life that can be expected from sealed-lead acid batteries.

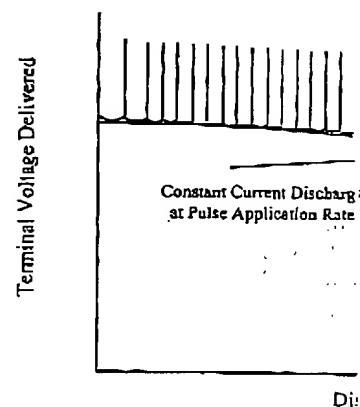
#### 9.4.2.3 Effect of Pulse Discharge on Capacity

In some applications, the battery is not called on to deliver a current continuously. Rather, energy is drawn from the battery in pulses. By allowing the battery to "rest" between these pulses, the total capacity available from the battery is increased. Figure 9-5 shows typical curves representing the voltage delivered as a function of discharged capacity for pulsed and constant discharge at the same rate.

For the pulsed curve, the upper line represents the open-circuit voltage and the lower line represents the voltages during the periods when the load



**FIGURE 9-4** Typical cell's capacity c



**FIGURE 9-5** Typical pulsed and const.

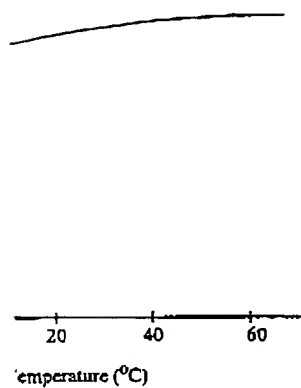
is connected. The use of discharged ca periods and shows only the periods of

#### 9.4.3 Charging

In general, experience with sealed-lead acid batteries shows that application problems are more likely to result from undercharging or overcharging. Since the starved-electrolyte condition is a result of undercharging, designers may want to overcharge, even at the expense of some capacity loss, to avoid overcharging, either in magnitude or duration.



## Circuit Block Design



a function of cell temperature

## Life

Lead acid batteries is almost always capacity. However, during the battery's life it reaches a stabilized value, which number of charge/discharge cycles or develop a battery's capacity depends on, a battery that is on charge at 0.1 C (of rated capacity) overcharge. The discharging at low rates. A battery's capacity will remain at or useful life. Batteries then will begin to their age and the duty to which they usually increases slowly with age until capacity, which often is defined as the the capacity variation with cycle life batteries.

## Life on Capacity

called on to deliver a current continuously in pulses. By allowing the battery capacity available from the battery is representing the voltage delivered as and constant discharge at the same

represents the open-circuit voltage during the periods when the load

## Rechargeable Batteries and Their Management 377

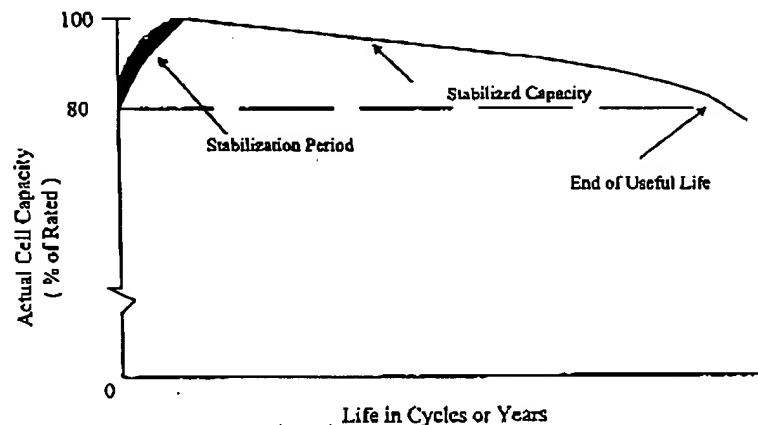


FIGURE 9-4 Typical cell's capacity during its life

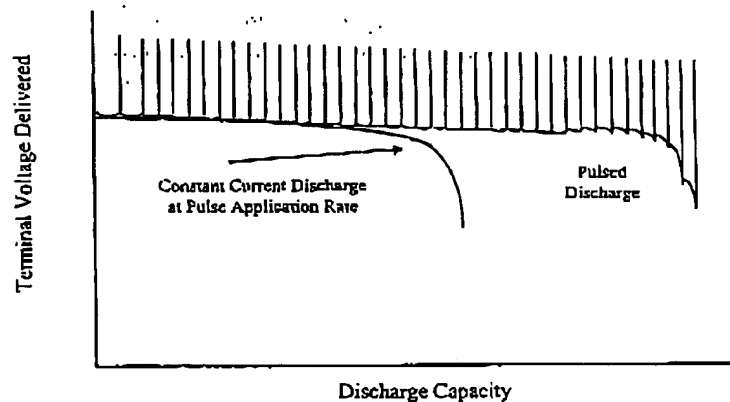
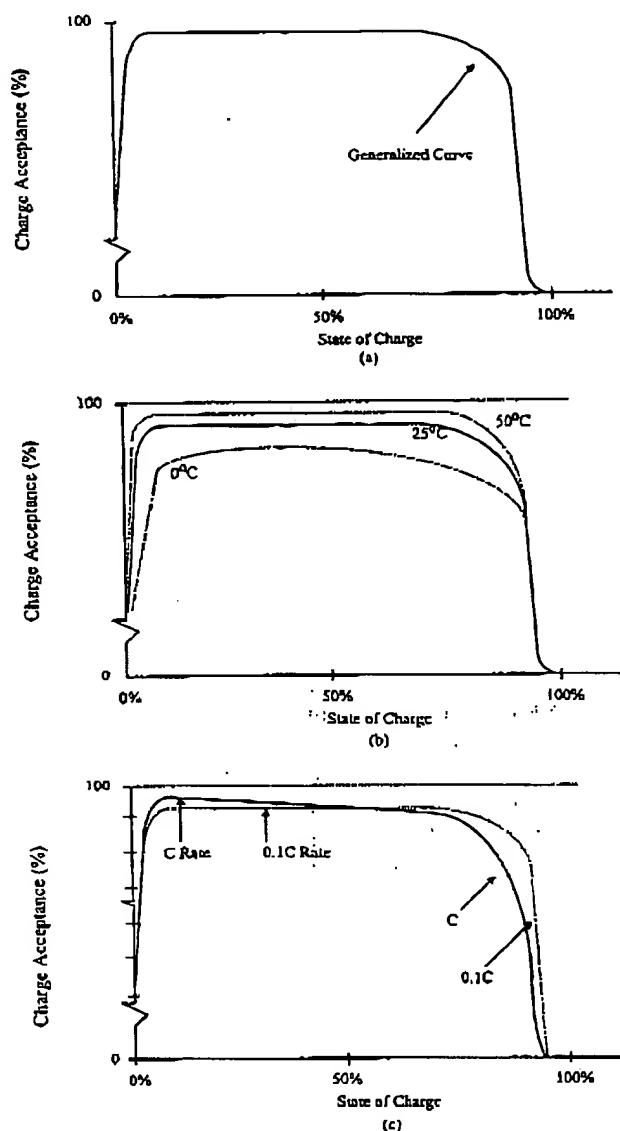


FIGURE 9-5 Typical pulsed and constant discharge curves

is connected. The use of discharged capacity as the abscissa eliminates the rest periods and shows only the periods of useful discharge.

## 9.4.3 Charging

In general, experience with sealed-lead acid cells and batteries indicates that application problems are more likely to be caused by undercharging than overcharging. Since the starved-electrolyte cell is relatively resistant to damage from overcharging, designers may want to ensure that the batteries are fully charged, even at the expense of some degree of overcharge. Obviously, excessive overcharging, either in magnitude or duration, still should be avoided.



**FIGURE 9-6** Charge acceptance: (a) effect of state of charge on charge acceptance, (b) charge acceptance at various temperatures, (c) charge acceptance at various charge rates

The charge acceptance of sealed lead-acid batteries is quite high, typically greater than 90% every ampere-hour of charge introduced. A fully charged cell can deliver 0.9 Ah to a load. Charge acceptance is affected by cell temperature, charge rate, and state of charge (Figure 9-6).

The state of charge of the cell, with which the cell will accept a charge, is the charge acceptance initially is quite low. As the cell is charged, it accepts current more readily, approaching 98% in some situations, until the cell approaches full charge.

As mentioned earlier, as the cell approaches full charge, the electrical energy begins generating gas, which is a problem. When the cell is fully charged, essential self-discharge phenomena is shown in Figure 9-6(a).

As with most chemical reactions, the rate of the reaction is higher at higher temperatures than at lower temperatures, as shown in Figure 9-6(b).

The starved-electrolyte sealed-lead-acid battery can accept a charge at low rates as long as the state of charge is not set too high. The cell can be charged at low rates when the state of charge is low.

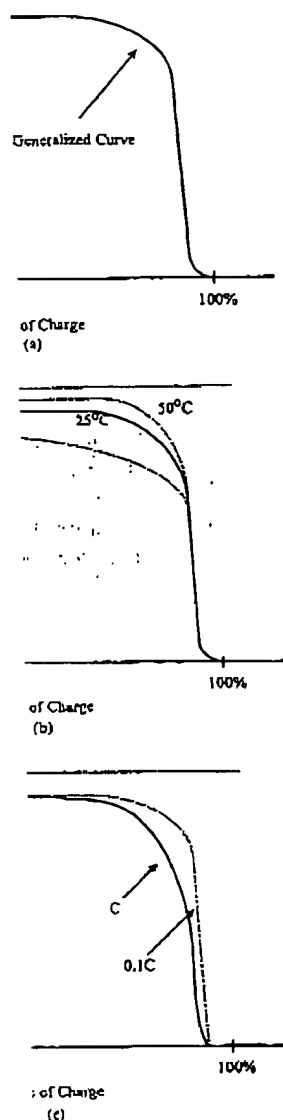
Figure 9-6(c) shows the generalized charge acceptance defined by charging rates. When examined at low charge rates, the cell can accept a charge.

In the starved-electrolyte sealed-lead-acid battery, the bulk of the gases is recombined and the cell can be charged at low rates.

## 9.5 Nickel-Cadmium Batteries

Sealed NiCd batteries are especially useful as a self-contained power source. Among the significant advantages of NiCd batteries are fast recharge capability, low self-discharge rates, and the ability to operate in any orientation with reasonable confidence.

## rcuit Block Design



of state of charge on charge acceptance,  
(c) charge acceptance at various charge

## Rechargeable Batteries and Their Management 379

The charge acceptance of sealed-lead acid batteries in most situations is quite high, typically greater than 90%. A 90% charge acceptance means that for every ampere-hour of charge introduced into the cell, the cell will be able to deliver 0.9 Ah to a load. Charge acceptance is affected by a number of factors including cell temperature, charge rate, state of charge, age, and the method of charging (Figure 9-6).

The state of charge of the cell, to some extent, will dictate the efficiency with which the cell will accept a charge. When the cell is fully discharged, the charge acceptance initially is quite low. As the cell becomes only slightly charged, it accepts current more readily and the charge acceptance jumps quickly, approaching 98% in some situations. The charge acceptance stays at a high level until the cell approaches full charge.

As mentioned earlier, as the cell becomes fully charged, some of the electrical energy begins generating gas, which represents a loss in charge acceptance. When the cell is fully charged, essentially, all the charging energy generates gas, except for the very small current that makes up for internal losses that otherwise would be manifested as self-discharge. A generalized curve representing these phenomena is shown in Figure 9-6(a).

As with most chemical reactions, temperature has a positive effect on the charging reactions in the sealed-lead acid cell. Charging is more efficient at higher temperatures than at lower temperatures, all other parameters being equal, as shown in Figure 9-6(b).

The starved-electrolyte sealed-lead cell charges very efficiently at most charging rates. The cell can accept a charge at accelerated rates (up to the C rate) as long as the state of charge is not so high that excessive gas is generated. And the cell can be charged at low rates with excellent charge acceptance.

Figure 9-6(c) shows the generalized curve of charge acceptance now further defined by charging rates. When examining these curves, note that, at high states of charge, low charge rates provide better charge acceptance.

In the starved-electrolyte sealed-lead acid cell at typical charging rates, the bulk of the gases is recombined and there is virtually no venting of gases from the cell if it is overcharged.

## 9.5 Nickel-Cadmium Batteries

Scaled NiCd batteries are especially well suited to applications where a self-contained power source increases the versatility or reliability of the product. Among the significant advantages of NiCd families are higher energy density and discharge rates, fast recharge capability, and long operating and storage life. This places NiCd families at the top of usage in the portable products. In addition, the NiCd batteries are capable of operating over a wide temperature range and in any orientation with reasonable continuous overcharge capability.

## 380 Modern Component Families and Circuit Block Design

## 9.5.1 Construction

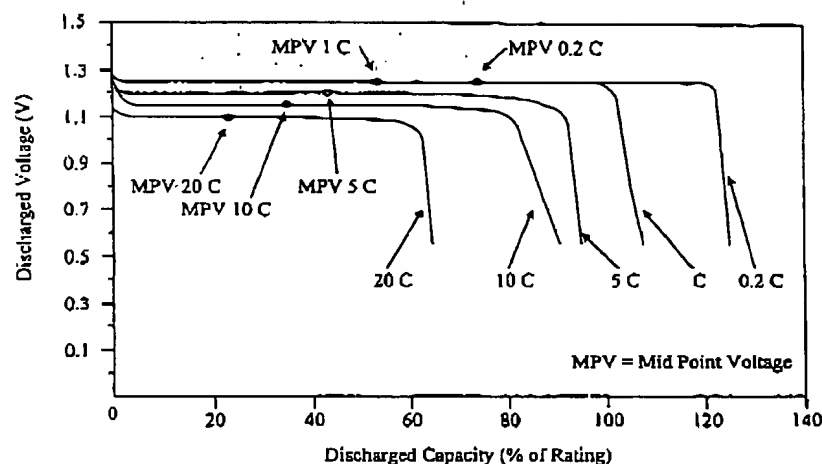
NiCd secondary batteries operate at 1.2 V, using nickel oxyhydroxide for the active material in the positive electrode. The active material of the negative electrode consists of cadmium, and an alkali solution acts as the electrolyte. In NiCd batteries, a reaction at the negative electrode consumes the oxygen gas that generates at the positive electrode during overcharging. The design prevents the negative electrode from generating hydrogen gas, permitting a sealed structure. NiCd batteries mainly adopt cylindrical or prismatic configurations.

## 9.5.2 Discharge Characteristics

The discharge voltage of a sealed NiCd cell typically remains relatively constant until most of its capacity is discharged. It then drops off rather sharply. The flatness and length of the voltage plateau relative to the length of discharge are major features of sealed NiCd cells and batteries. The discharge curve, when scaled by considering the effects of all the application variables, provides a complete description of the output of a battery. Differences in design, internal construction, and conditions of actual use of cell affect the performance characteristics. As an example, Figure 9-7 illustrates the typical effect of discharge rate.

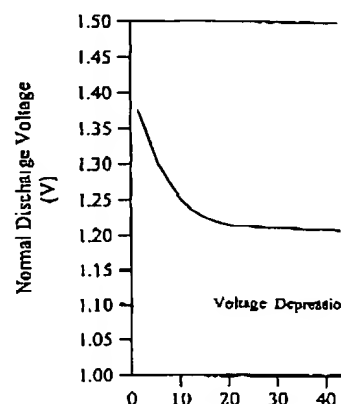
## 9.5.3 Charge Characteristics

Nickel-cadmium batteries are charged by applying a current of proper polarity to the terminals of the battery. The charging current can be pure direct current (DC) or it may contain a significant ripple component such as half-wave or full-wave rectified current.



**FIGURE 9-7** Discharge curves for NiCd cells; (a) typical curves at 23°C, (b) voltage depression effect

Recharge



**FIGURE 9-7** Continued

This section on charging sealed rates as multiples (or fractions) of the bc categorized into descriptive terms, charge, or trickle charge as shown in

When a nickel-cadmium battery i to converting the active material to a also goes to converting active materia is lost in parasitic side reactions.

Figure 9-8 shows the charge accep no charge acceptance loss, would be to the cell could be retrieved on discl accept charge at different levels of efi of the cell, as shown by the bottom ci

Figure 9-8 describes this perfor behavior (zones 1, 2, 3, and 4). Each mechanisms responsible for loss of ch

**TABLE 9-2** Categories of rates for cha

Method of Charging	Charge rate (multiples of C rate)
Standard	0.05
	0.1
Quick	0.2
	0.25
	0.33
Fast	1
	2
	4
Trickle	0.02–0.1

## Unit Block Design

V, using nickel oxyhydroxide for the active material of the negative solution acts as the electrolyte. In recharging, the design prevents the gas, permitting a sealed structure. ismistic configurations.

d cell typically remains relatively flat. It then drops off rather sharply. relative to the length of discharge batteries. The discharge curve, when application variables, provides a variety. Differences in design, internal cell affect the performance characteristics. the typical effect of discharge rate.

y applying a current of proper power, charging current can be pure direct or ripple component such as half-wave

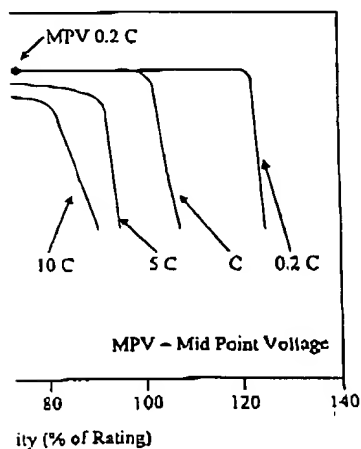


FIGURE 9-7 Continued

This section on charging sealed nickel-cadmium batteries refers to charging rates as multiples (or fractions) of the C rate. These C rate charging currents can be categorized into descriptive terms, such as standard charge, quick charge, fast charge, or trickle charge as shown in Table 9-2.

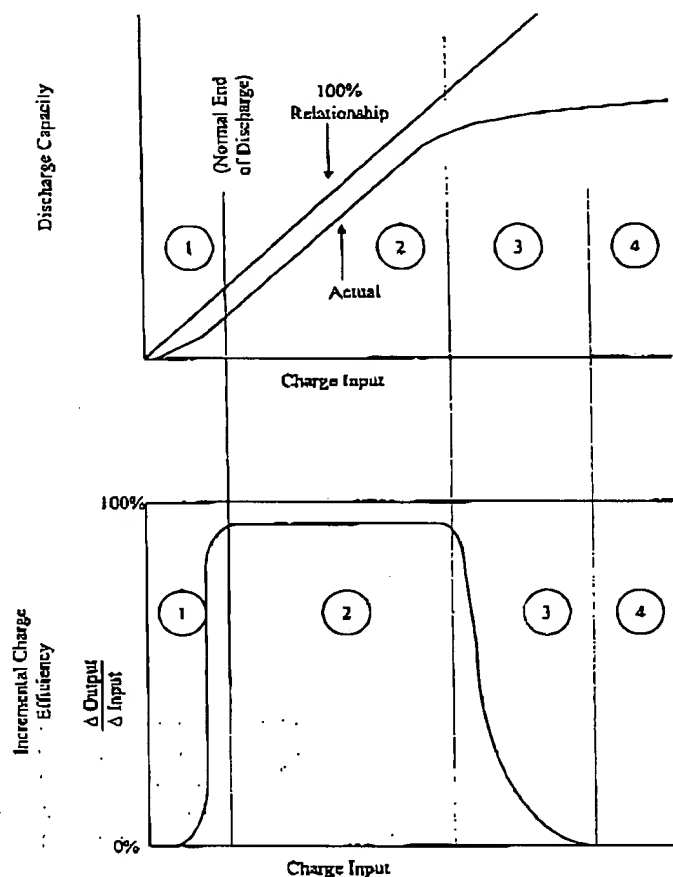
When a nickel-cadmium battery is charged, not all of the energy input goes to converting the active material to a usable (chargeable) form. Charge energy also goes to converting active material into an unusable form, generates gas, or is lost in parasitic side reactions.

Figure 9-8 shows the charge acceptance of NiCd cells. The ideal cell, with no charge acceptance loss, would be 100% efficient. All the charge delivered to the cell could be retrieved on discharge. But nickel-cadmium cells typically accept charge at different levels of efficiency, depending on the state of charge of the cell, as shown by the bottom curve of Figure 9-8.

Figure 9-8 describes this performance for successive types of charging behavior (zones 1, 2, 3, and 4). Each zone reflects a distinct set of chemical mechanisms responsible for loss of charge input energy.

TABLE 9-2 Categories of rates for charging NiCd cell

Method of Charging	Charge rate (multiples of C rate)	Recharge Time (hours)	Charge Control
Standard	0.05	36-48	Not required
	0.1	16-20	
Quick	0.2	7-9	Not required
	0.25	5-7	
	0.33	4-5	
Fast	1	1.2	Required
	2	0.6	
	4	0.3	
	0.02-0.1	Used for maintaining a fully charged battery	
Trickle			



**FIGURE 9-8** Charge acceptance of a sealed NiCd cell at 0.1 C and 23°C

In zone 1, a significant portion of the charge input converts some of the active material mass to an unusable form; that is, charged material not readily accessible during medium- or high-rate discharges, particularly in the first few cycles. In zone 2, the charging efficiency is only slightly less than 100%; small amounts of internal gas and parasitic side reactions are all that prevent the charge from being totally efficient. Zone 3 is transition region.

As the cell approaches a full charge, the current input shifts from charging positive active material to generating oxygen gas. In the overcharge region, zone 4, all the current coming into the cell generates gas. In this zone, the charging efficiency is practically none.

The boundaries between zones 1, 2, 3, and 4 are indistinct and vary depending on cell temperature, construction, and charge rate. The level of charge

acceptance in zones 1, 2, and 3 also is rate. For details, see Gates Energy Pr

### 9.5.4 Voltage Depression

When some NiCd batteries are cycled and overcharging, cell voltage of the capacity is consumed. This is the resulting lower voltage may be proper system operation, giving the in Figure 9-7(b)). If cells are exposed to atures, and this is quite common, the the normal cell voltage. Voltage depi tion that disappears when the cell is voltage depression effect sometimes and clearing the same by charging an

### 9.6 Nickel-Metal Hydride I

For those battery users who need willing to pay a higher price, an op which offer a significant increase in NiCd cell technology to a new chem applications such as notebook comput NiMH batteries entered the market in

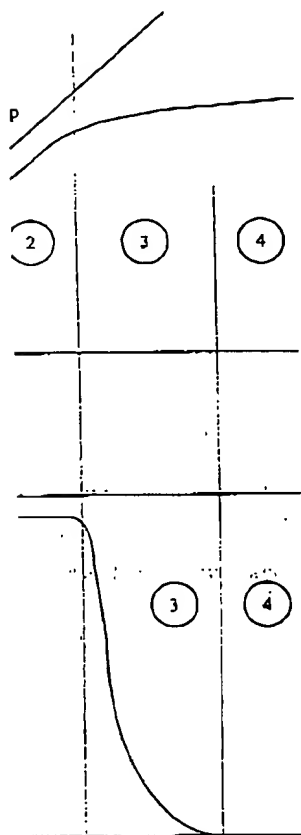
In many ways, nickel-metal hydr They use nickel for the positive elect hydrogen-absorbing alloy, for the neg of 1.2 V, they provide high capacity, i

The NiCd cell is more tolerant NiMH cells. NiCd cells hold their cha will withstand 500–2000 charge/discha for NiMH cells. Further, NiCd cells v NiMH cells.

On the other hand, NiMH cells sel that NiCd cells sometimes do. As with applications are higher than those of Ni 1993; Briggs, 1994).

The voltage profile of NiMH cell of the NiCd cells. NiMH cells' open-c discharge rates, NiMH cells' output vol have relatively constant output voltage typical graph from a battery company. NiCd and 1100 mAh NiMH AA cells greater capacity results in approximate

circuit Block Design



NiCd cell at 0.1 C and 23°C

charge input converts some of the hat is, charged material not readily charges, particularly in the first few only slightly less than 100%; small ctions are all that prevent the charge tion region.

e current input shifts from charging gen gas. In the overcharge region, ll generates gas. In this zone, the

, and 4 are indistinct and vary de- nd charge rate. The level of charge

## Rechargeable Batteries and Their Management 383

acceptance in zones 1, 2, and 3 also is influenced by cell temperature and charge rate. For details, see Gates Energy Products (1992).

### 9.5.4 Voltage Depression Effect

When some NiCd batteries are subjected to numerous partial discharge cycles and overcharging, cell voltage decreases below, 1.05 V/cell before 80% of the capacity is consumed. This is called the **voltage depression effect**; and the resulting lower voltage may be below the minimum voltage required for proper system operation, giving the impression that the battery has worn out (see Figure 9-7(b)). If cells are exposed to overcharging, particularly at higher temperatures, and this is quite common, the voltage may be about 150 mV lower than the normal cell voltage. Voltage depression is an electrically reversible condition that disappears when the cell is completely discharged and recharged. The voltage depression effect sometimes is called erroneously the **memory effect**, and clearing the same by charging and discharging is called conditioning.

## 9.6 Nickel-Metal Hydride Batteries

For those battery users who need high power in a small package and are willing to pay a higher price, an option is the nickel-metal hydride families, which offer a significant increase in cell power density. These extensions of NiCd cell technology to a new chemistry have become popular with product applications such as notebook computers and cellular phones. The first practical NiMH batteries entered the market in 1990.

In many ways, nickel-metal hydride batteries are the same as NiCd types: They use nickel for the positive electrode but a recently developed material, a hydrogen-absorbing alloy, for the negative electrode. With an operating voltage of 1.2 V, they provide high capacity, more energy density than NiCd models.

The NiCd cell is more tolerant of fast recharging and overcharging than NiMH cells. NiCd cells hold their charge longer than NiMH cells. NiCd cells will withstand 500–2000 charge/discharge cycles, compared to about 500 cycles for NiMH cells. Further, NiCd cells withstand a wider temperature range than NiMH cells.

On the other hand, NiMH cells seldom exhibit the notorious "memory effect" that NiCd cells sometimes do. As with any new technology, the prices for NiMH applications are higher than those of NiCds (Small, 1992; Eagar, 1991; Furukawa, 1993; Briggs, 1994).

The voltage profile of NiMH cells during discharge is very similar to that of the NiCd cells. NiMH cells' open-circuit voltage is 1.3–1.4 V. At moderate discharge rates, NiMH cells' output voltage is 1.2 V. Both NiCd and NiMH cells have relatively constant output voltage during their useful service. Figure 9-9 is a typical graph from a battery company, comparing the output voltage of 700 mAh NiCd and 1100 mAh NiMH AA cells under load. Note that the NiMH cell's greater capacity results in approximately 50% longer service life.

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Rechargeable

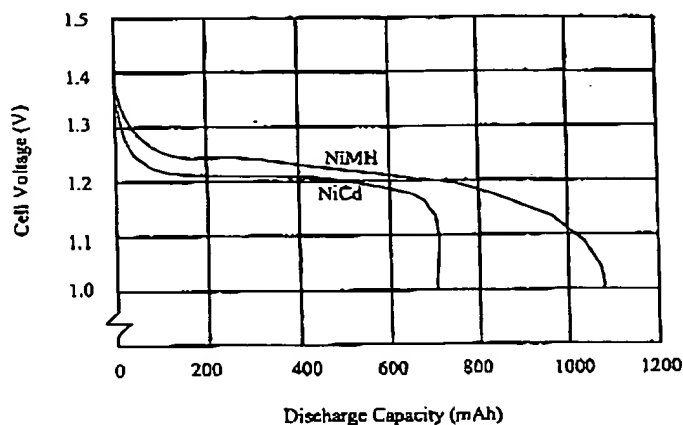


FIGURE 9-9 Discharge characteristics of NiCd and NiMH batteries

Figure 9-10 is another typical battery company graph showing that NiCd and NiMH batteries and cells charge in a similar fashion as well. However, the little bumps at the end of the two cell's charge curves bare closer examination. You always will see these negative excursions, even though absolute cell voltages vary significantly with temperature.

The negative excursions signal a fully charged cell more or less independent of temperature, a useful quirk that sophisticated battery chargers exploit. Note that the NiCd cell's negative-going voltage excursion after reaching a full charge is more pronounced than that of the NiMH cell.

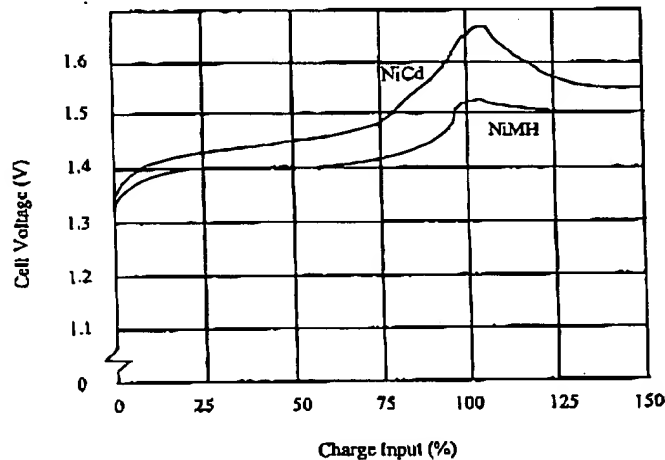


FIGURE 9-10 Battery voltage at the achievement of 100% charge

There are several reasons for recharging:

- NiCd batteries contain cadmium, a toxic material.
- NiMH has nearly the same operating life as NiCd batteries.
- NiMH batteries have 30–40% higher capacity than NiCd batteries.
- NiMH batteries have a 90-minute recharge time.

## 9.7 Lithium-Ion Batteries

The demand for portable systems is increasing. Meeting these goals requires improved battery technology. Li-ion and NiCd and NiMH systems.

Li-ion is a promising technology. It is twice the size and weight of a battery pack. Meeting these goals requires improved battery technology. Li-ion and NiCd and NiMH systems.

The first noticeable difference between Li-ion and NiCd is the higher internal impedance of

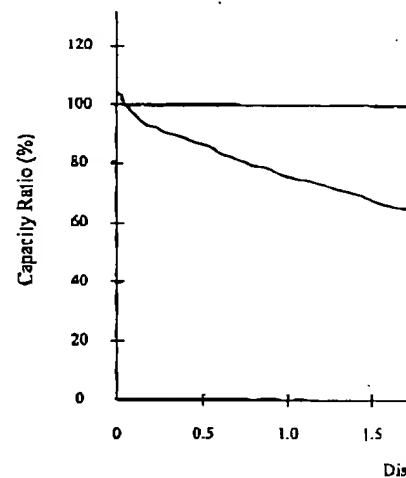


FIGURE 9-11 Li-ion and NiCd capacity



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